

# REVISTA

DE PIELĂRIE ÎNCĂLȚĂMINTE

Leather and Footwear Journal

June / Iunie 2026  
Volume / Volumul 26  
Issue / Ediția 2

**INCDTP - SUCURSALA INSTITUTUL DE CERCETĂRI PIELĂRIE ÎNCĂLȚĂMINTE**  
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*Revista de Pielărie Încălțăminte / Leather and Footwear Journal* is acknowledged in Romania by the National University Research Council (CNCIS) in B+ Category (code 565), and is indexed in Chemical Abstracts Service (CAS) Database, USA, CAB Database (CAB International, UK), Elsevier's Compendex and SCOPUS, CrossRef, EBSCO, ProQuest, Index Copernicus, CiteFactor, Research Bible, and listed in Matrix for the Analysis of Journals (MIAR), Electronic Journals Library (EZB), Journal TOCs, Root Indexing, Scilit, and SCPIO.

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Hard copies of journal issues are available for purchase at subscription rates of 160 EURO for companies and 100 EURO for individual subscribers, while the rate for a single issue is 40 EURO. Subscriptions (include mailing costs) can be made at the editorial office, to the following address:

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Title DOI: <https://doi.org/10.24264/ljf>





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ISSN: 1583-4433

Volume 26, No. 2, June 2026

<https://doi.org/10.24264/lfj.26.2>

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# DECORATIVE FINISHES IN FOOTWEAR DESIGN, SIGNIFICANCE AND CURRENT TRENDS

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Received: 08.12.2025

Accepted: 06.05.2026

<https://doi.org/10.24264/lfj.26.2.1>

## DECORATIVE FINISHES IN FOOTWEAR DESIGN, SIGNIFICANCE AND CURRENT TRENDS

**ABSTRACT.** The footwear industry faces a dynamic interplay between evolving consumer demands for aesthetic individuality, functional performance, and sustainable practices. While decorative finishes historically served as markers of cultural identity and status, modern challenges—such as balancing technological innovation with environmental responsibility, mitigating greenwashing risks, and integrating advanced customization—highlight a gap in systematic research on how these elements collectively shape contemporary design paradigms. This study examines the historical evolution, cultural significance, and contemporary innovations of decorative finishes in footwear design, emphasizing their role in merging aesthetics with functionality. Through a comprehensive literature review and integrative analysis of academic and industry sources, the research categorizes decorative finishes into six classes: textures, ornaments, patterns, surface treatments, colors, and specialized effects. The study highlights current innovations driven by sustainability and technology which enhance customization and reduce environmental impact. Social media and influencers amplify trends, transforming niche designs into mainstream demand through viral visibility. However, challenges persist, including balancing aesthetic complexity with durability, mitigating greenwashing risks, and integrating wearable tech under regulatory constraints. The findings underscore the dual imperative for the footwear industry: advancing eco-conscious materials and leveraging emerging technologies like generative AI and augmented reality for personalized designs.

**KEY WORDS:** footwear design, creative design, sustainability, design customization, technological innovation, brand identity

## FINISAJELE DECORATIVE ÎN DESIGNUL DE ÎNCĂLȚĂMINTE: SEMNIFICAȚIE ȘI TENDINȚE ACTUALE

**REZUMAT.** Industria de încălțăminte se confruntă cu o interacțiune dinamică între cerințele în continuă evoluție ale consumatorilor în ceea ce privește individualitatea estetică, performanța funcțională și practicile durabile. În timp ce finisajele decorative au servit de-a lungul timpului ca marcatori ai identității culturale și ai statutului social, provocările moderne — precum echilibrarea inovației tehnologice cu responsabilitatea față de mediu, atenuarea riscurilor de greenwashing și integrarea personalizării avansate — evidențiază o lacună în cercetarea sistematică privind modul în care aceste elemente modelează colectiv paradigmele de design contemporane. Acest studiu examinează evoluția istorică, semnificația culturală și inovațiile contemporane ale finisajelor decorative în designul încălțăminte, subliniind rolul acestora în îmbinarea esteticii cu funcționalitatea. Printr-o revizuire cuprinzătoare a literaturii de specialitate și o analiză integrativă a surselor academice și industriale, cercetarea clasifică finisajele decorative în șase categorii: texturi, ornamente, modele, tratamente de suprafață, culori și efecte specializate. Studiul evidențiază inovațiile actuale determinate de sustenabilitate și tehnologie, care îmbunătățesc personalizarea și reduc impactul asupra mediului. Rețelele sociale și influencerii amplifică tendințele, transformând designurile de nișă în cerere mainstream prin vizibilitate virală. Cu toate acestea, provocările persistă, printre acestea numărându-se găsirea unui echilibru între complexitate estetică și durabilitate, reducerea riscurilor de „greenwashing” și integrarea tehnologiilor portabile în contextul constrângerilor normative. Concluziile subliniază o dublă necesitate pentru industria de încălțăminte: promovarea materialelor ecologice și valorificarea tehnologiilor emergente, precum inteligența artificială generativă și realitatea augmentată, pentru crearea de modele personalizate.

**CUVINTE CHEIE:** design de încălțăminte, design creativ, sustenabilitate, personalizarea designului, inovare tehnologică, identitate de brand

## FINITIONS DÉCORATIVES DANS LA CONCEPTION DE CHAUSSURES : IMPORTANCE ET TENDANCES ACTUELLES

**RÉSUMÉ.** L'industrie de la chaussure est confrontée à une interaction dynamique entre les exigences en constante évolution des consommateurs en matière d'individualité esthétique, de performances fonctionnelles et de pratiques durables. Alors que les finitions décoratives ont historiquement servi de marqueurs d'identité culturelle et de statut social, les défis modernes — tels que l'équilibre entre innovation technologique et responsabilité environnementale, l'atténuation des risques de greenwashing et l'intégration d'une personnalisation avancée — mettent en évidence un manque de recherche systématique sur la manière dont ces éléments façonnent collectivement les paradigmes du design contemporain. Cette étude examine l'évolution historique, la signification culturelle et les innovations contemporaines des finitions décoratives dans la conception de chaussures, en soulignant leur rôle dans la fusion de l'esthétique et de la fonctionnalité. Grâce à une revue exhaustive de la littérature et à une analyse intégrative de sources universitaires et industrielles, la recherche classe les finitions décoratives en six catégories : textures, ornements, motifs, traitements de surface, couleurs et effets spécialisés. L'étude met en avant les innovations actuelles portées par la durabilité et la technologie, qui améliorent la personnalisation et réduisent l'impact environnemental. Les réseaux sociaux et les influenceurs amplifient les tendances, transformant des designs de niche en demande populaire grâce à une visibilité virale. Cependant, des défis subsistent, notamment celui de concilier complexité esthétique et durabilité, d'atténuer les risques de « greenwashing » et d'intégrer les technologies portables dans le respect des contraintes réglementaires. Ces conclusions soulignent le double impératif auquel est confrontée l'industrie de la chaussure : promouvoir

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les matériaux respectueux de l'environnement et tirer parti des technologies émergentes telles que l'IA générative et la réalité augmentée pour créer des designs personnalisés.

MOTS-CLÉS : conception de chaussures, design créatif, durabilité, personnalisation du design, innovation technologique, identité de marque

## INTRODUCTION

Decorative finishes in shoe design refer to the artistic and technical embellishments that elevate footwear beyond mere utility, turning them into statements of personal style. Techniques such as embroidery, unique material applications, and surface treatments are essential in fashion, showcasing cultural trends and innovations in design.

Since the emergence of design aesthetics in the mid-19<sup>th</sup> century [1], people have continually sought to incorporate its principles into footwear design, including shoes and boots. Only in the mid-to-late 20<sup>th</sup> century, following influential art movements, did footwear and accessory design truly flourish through the blending of aesthetic principles with other artistic disciplines. The evolution of design during the late 19<sup>th</sup> and 20<sup>th</sup> centuries was heavily shaped by profound social changes, conflicts, and technological breakthroughs [2].

As a fast-paced and transformative sector, the fashion industry relies heavily on creative breakthroughs to steer trends and buyer behavior [3]. Notably, decorative finishing techniques in shoe and accessory design have gained prominence [4], serving dual purposes: boosting aesthetic value while enhancing practicality, resilience, and market success.

The visual appeal of footwear is a key factor in determining the popularity and market success of brands and styles aimed at young consumers [5]. Decorative finishes are crucial in shoe and accessory design, elevating practical items into works of art. This process employs various methods and materials to improve both the look and feel of fashion products. Whether through detailed embroidery, beadwork, metallic embellishments, or distinctive textures, decorative finishing helps establish a brand's identity, influence trends, and convey a sense of luxury or avant-garde style.

The essence of the study: An investigation of decorative finishes in footwear design, tracing their historical evolution, classifying their types, evaluating their functional and aesthetic roles, and identifying current trends, challenges, and future directions.

Specific research tasks:

1. To trace the historical development of decorative finishes in footwear (Chinese and global perspectives).
2. To propose a comprehensive classification of decorative finishes into six categories.
3. To evaluate decorative techniques based on defined criteria (see below).
4. To analyze the factors influencing the choice of decorative finishes across different historical periods and in contemporary design.
5. To identify current trends (sustainability, technology, customization) and future challenges.

Having established the study's aims—to investigate the historical evolution, categorize decorative techniques, and analyze their influence on brand identity, consumer choices, and market trends—the next logical step is to describe how these objectives were pursued. The following section details the methodological framework employed, including the literature search strategy, database selection, and analytical synthesis approach. This transparency ensures that the subsequent historical review and classification rest on a replicable and systematic foundation.

## RESEARCH METHODOLOGY

The study began by establishing a structured framework to outline the scope and content sources. A comprehensive literature search followed, involving database reviews, concept mapping, and synthesis methodologies. Key databases such as Web of Science, Google

Scholar, Bing Scholar, and general search engines were systematically explored.

To enhance content discovery, an integrative constrained snowball approach was employed, consisting of four phases: analysis and synthesis, comparative-historical evaluation, and empirical analysis. Manual screening was then conducted to exclude publications that did not meet the predefined inclusion criteria. The search was not restricted by time period, though decorative or garment-related finishing techniques were deliberately excluded from the study.

The succeeding presentation is structured as follows, the study begins with a historical review of decorative finishes in footwear, examining both Chinese and global perspectives. Next, it explores the classification of these finishes, identifying and analyzing six major categories. The discussion then highlights the importance of decorative finishes in footwear design, followed by an analysis of current industry trends. Finally, the paper addresses the challenges and future prospects in the field of decorative footwear finishes.

With the methodological framework established, the study now turns to the first substantive area of inquiry: the historical evolution of decorative finishes. Understanding how and why embellishment practices emerged across different civilizations—from ancient China to medieval Europe—provides essential context for the contemporary classification and trend analysis that follow. The next section traces this trajectory, highlighting cultural, technological, and social forces that have shaped footwear decoration over centuries.

## **HISTORICAL OVERVIEW OF DECORATIVE FINISHES IN FOOTWEAR**

The artistry of decorative finishes in footwear and accessories has undergone profound transformations across centuries, mirroring shifts in style, materials, craftsmanship, and societal values. In China, political influences have played a pivotal role in shaping shoe and accessory fashion throughout history. From as

early as the Shang and Zhou dynasties (circa 1600 BCE–256 BCE), successive Chinese regimes established formal regulations governing the wearing of shoes and accessories [6].

During the Qin and Han dynasties (221 BCE–220 CE), distinct footwear styles were designated for specific occasions: sacrificial attendants wore slippers, court officials donned boots, swallow-style garments were paired with sandals, and clogs were worn outdoors. The Tang Dynasty (618–907 CE) saw both officials and commoners wearing boots, though with subtle style variations, while women favored fashionable soft-soled hollow Jin-leg boots. The controversial practice of foot binding, which originated during Emperor Li Yu's reign in the Tang period [7], began when a concubine bound her feet in silk to dance on a golden lotus platform. This cultural tradition involved the painful constriction of young girls' feet to create artificially small, pointed shapes, embodying contemporary standards of beauty and feminine ideals [8].

This custom gained widespread popularity during the Song Dynasty (960–1279 CE), growing into an enduring cultural practice that persisted for generations. Footwear for bound feet, called "Lotus shoes," mirrored the graceful shape of a lotus flower. Crafted from delicate materials like silk or cotton, these shoes featured detailed embroidery and were often decorated with precious stones. They came in both flat-soled and heeled variations to accommodate individual preferences [9].

During the Song Dynasty (960–1279 CE), Chinese footwear exhibited distinct gendered designs: men wore small-headed leather shoes, while women's styles featured rounded, flat, or pointed toes. These shapes were rooted in the cosmological "Heaven and Earth" philosophy. Square-toed shoes for men embodied yang energy, symbolizing celestial power and nobility descending from the heavens. Conversely, women's round-toed designs represented the earth's harmony, conveying gentleness, cyclical nature, and traditional feminine virtues [10].



Figure 1. (a) Chinese Lotus Shoes [11], (b) Qing Dynasty flower pot bottom shoes [12]

Throughout the Ming Dynasty (1368-1644 CE), footwear styles reflected social status and occupation: officials donned Zao boots or cloud-head shoes, Confucian scholars wore distinctive black double-beam shoes, while commoners typically wore cloth shoes, bushy footwear, or straight-seamed cowhide boots. Women with bound feet wore elevated camphor-wood bow shoes. As illustrated in Fig. 1(a) and (b), intricately embroidered lotus shoes exemplify the period's craftsmanship.

During China's final imperial dynasty, the Qing (1616-1912 CE), footwear denoted rank and occasion: emperors wore square-toe boots for court appearances [13], officials donned black satin boots, soldiers wore practical "creeper" boots, and high-ranking mandarins sported distinctive dental boots. This period saw a gradual evolution in toe shapes from square to pointed toes. Throughout Chinese history, embroidery remained the primary decorative technique for footwear, showcasing exquisite craftsmanship across social classes.

Throughout the 20<sup>th</sup> century and into the modern era, China systematically developed its footwear manufacturing sector, expanding production of leather, cloth, and rubber shoes. Following the establishment of the People's Republic of China, the nation methodically built a complete industrial framework for footwear production, with leather, fabric, and plastic shoes constituting its core product categories.

Globally, footwear and accessory trends have been profoundly shaped by artistic movements and design philosophies. Concurrently, religious influences, political factors, economic conditions, and sociocultural environments have equally contributed to their

evolution, creating a complex interplay of forces that drive innovation in this sector.

Evidence of diverse techniques and material processing indicates that prehistoric societies had developed sophisticated shoemaking skills by the Mesolithic era, approximately 9,500 years ago. While archaeological findings in Europe and North America predate those in China, researchers discovered 6,200-year-old woven shoes in Spain's Cueva de los Murciélagos (Bat Cave) in Andalusia, underscoring the early global spread of footwear innovation [14].

Archaeological evidence reveals that early civilizations employed footwear as social markers. In Egyptian and Mesopotamian societies, simple sandals were sometimes decorated with status-indicating colors or symbolic decorations [15]. Meanwhile, Greek artisans pioneered woven footwear using organic materials like straw, plant fibers, and papyrus as early as the 5<sup>th</sup> century CE, predating medieval shoemaking traditions [16, 17].

In medieval Europe, footwear transcended mere utility, becoming a canvas for religious symbolism and social expression. Decorated shoes and accessories—such as belts and pouches—frequently featured sacred iconography or heraldic designs, mirroring the period's spiritual and hierarchical values. Among the elite, elongated poulaines (also called Cracow shoes) emerged as sartorial status symbols, meticulously embellished with intricate embroidery and precious stones. These pointed shoes ultimately became one of the most distinctive footwear styles of the Middle Ages.

During the late medieval period, Europe's footwear industry experienced significant growth, marked by the emergence



of diverse styles including Polona shoes, platform footwear, mid-calf boots, knight boots, and slippers. These designs not only served practical purposes tied to occupation and environment but also functioned as important markers of social identity and fashion trends. By the 18<sup>th</sup> century, shoe buckles had become particularly emblematic, reflecting the period's cultural values, social hierarchies, and aesthetic preferences [18].

The Renaissance period witnessed a transformation in footwear aesthetics as sartorial extravagance reached new heights. Shoemakers increasingly incorporated sumptuous textiles like silk, velvet, and brocade into their designs, while elaborate embellishments including intricate embroidery, delicate lacework, and gilded threading became hallmarks of luxury footwear. Distinctive ornamental elements such as fabric rosettes, satin bows, and silk ribbons further elevated these creations into wearable works of art.

Between 1850 and 1940, footwear design transitioned from ornate elegance to functional simplicity, reflecting both industrial advancements and revolutionary societal changes. This era of comparative geopolitical stability enabled extensive trade between Europe and Eastern nations, coinciding with continued colonial expansion into Southeast Asia and Oceania. Consequently, cultural artifacts from China and Pacific regions significantly influenced European material culture during this transformative period.

Since the Industrial Revolution, footwear manufacturing has diversified into distinct categories based on production techniques, including glued, vulcanized, injection-molded, stitched, and assembled shoes [19]. Similarly, material-based classification systems emerged, differentiating leather shoes, athletic footwear, fabric shoes, plastic shoes, and rubber shoes, reflecting advancements in both technology and material science.

The United States pioneered industrialized footwear production, where mechanization significantly lowered manufacturing costs, while Europe maintained traditional handcrafted shoemaking until the late 1800s. The rise of modern factories transformed footwear production from artisanal

craftsmanship to mass manufacturing. Entering the modern era, shoe designs diversified in response to evolving fashion trends, with distinctive styling and brand differentiation becoming increasingly prominent.

Contemporary fashion trends and growing consumer demand for customization have driven significant innovation in decorative finishing techniques. Current methods include both traditional approaches—such as carving, weaving, embroidery, and inlay—and advanced technologies like 3D printing, laser engraving, rhinestoning, embossing, and watermarking. These sophisticated processes enable intricate designs and complex structures, enhancing both the artistic value and personalization potential of modern footwear.

Footwear and accessory decoration remains an evolving synthesis of heritage craftsmanship and technological progress, reflecting both cultural traditions and material innovations. Cutting-edge scientific advancements have significantly expanded creative possibilities, enabling increasingly sophisticated and diverse approaches to shoe design and manufacturing [20].

The historical trajectory reveals a remarkable proliferation of techniques, materials, and cultural meanings—from embroidered lotus shoes in imperial China to laser-engraved sneakers today. This rich diversity, while testament to human creativity, presents a challenge for designers and researchers seeking to organize and apply these embellishments systematically. Without a structured framework, the vast array of possibilities risks becoming overwhelming. The following section therefore proposes a taxonomic classification of decorative finishes into six principal categories, providing a practical tool for analyzing historical and contemporary practices alike.

## CLASSIFICATION OF DECORATIVE FINISHES IN FOOTWEAR

Footwear finishing encompasses diverse technical processes that elevate both aesthetic appeal and product durability. Essential methods include surface treatments

like sanding, staining, and burnishing, as well as protective applications such as dyeing, polishing, and coating—each contributing to the refinement of visual characteristics and structural integrity in finished shoes.

This research systematically classifies decorative footwear finishes into six primary categories (shown in Figure 2): (1) texture treatments (e.g., patina, sueding), (2) addition of ornaments (e.g. Beading, rhinestones, metallic accents), (3) patterned designs (floral,

geometric, cultural motifs), (4) surface treatments (e.g. burnishing, polishing, sanding), (5) color applications (vibrant hues, earth tones, multicolor effects), and (6) special embellishments (including holographic and iridescent finishes). In today's footwear industry, which prioritizes meticulous craftsmanship and precision, finishing expertise plays a crucial role in enhancing aesthetic appeal, durability, and product quality.



Figure 2. Classification of decorative finishes in footwear design

### Textures

Texture describes the surface characteristics of a material as perceived through touch, encompassing qualities such as roughness, smoothness, softness, or hardness [21]. In contemporary textile evaluation, tactile assessment primarily relies on human sensory panels using hand-feel tests [22, 23]. In footwear design, texture serves dual purposes – contributing both to visual appeal and functional performance – and can be achieved through diverse technical processes and material sources.

### Addition of Ornaments

Footwear ornaments constitute decorative components applied to shoes for aesthetic enhancement, cultural expression, or symbolic significance [24]. These embellishments—historically prevalent across diverse cultures—function as visual markers of social status, personal identity, artistic tradition, and contemporary fashion. They encompass functional-decorative elements (buckles, laces, brooches) and textile-based adornments (embroidery, appliqué,

incorporating materials ranging from rhinestones and pearls to metallic accents.

### Patterns

In artistic design, patterns emerge through the systematic repetition and organization of visual elements, achieved by arranging shapes, lines, and forms in recurring sequences [25]. This repetition may occur identically or through defined transformations such as mirror symmetry [26]. Footwear decoration employs diverse pattern types, including geometric configurations (symmetrical or asymmetrical arrangements of squares, triangles, diamonds, and circles), floral motifs, animal-inspired designs, and culturally significant symbols. These patterns are realized through various application techniques—stitching, embossing, printing, and laser cutting—each contributing distinct visual interest and enhancing the shoe's aesthetic value.

### Surface Treatments

Surface treatments perform dual functional and aesthetic roles in material engineering. These techniques primarily modify visual properties through textural alterations (matte/gloss finishes) and color enhancement.

More critically, they enhance material performance by: (1) preventing corrosion and fraying [27], (2) modifying mechanical characteristics (electrical conductivity, wear resistance, friction properties), and (3) increasing product longevity and reliability. Recent advancements include innovative self-cleaning surface technologies [28].

### Colours

Color and form constitute the most visually dominant product attributes, significantly influencing consumer purchasing behavior [29]. In footwear design, color serves critical functional, aesthetic, and symbolic roles—often determining product acceptance or rejection [30]. High-quality leather with superior color and texture is particularly valued as a marker of sophistication and status [31]. Manufacturers employ diverse finishing techniques—including dyeing, painting, printing, and laminating—to achieve precise color effects that enhance visual appeal and marketability.

### Specialized Effects

Specialized effects in decorative finishing refer to unique visual, tactile, or functional enhancements applied to footwear materials to improve their aesthetic appeal, distinctiveness, or performance. These effects are achieved through various techniques, treatments, or materials and are defined by their specific characteristics. These specialized effects combine creativity and technical innovation, enhancing the visual appeal and uniqueness of footwear. Examples include Holographic or Iridescent Textures used in the promotion of

luxury items, and in some cases the hologram is used as part of anti-counterfeiting or traceability of luxury items [32].

### Evaluation Criteria for Decorative Techniques

To systematically assess the diverse decorative finishing techniques identified in the literature, this study applies an evaluation framework consisting of six criteria: aesthetic impact (visual appeal, distinctiveness, and alignment with brand or cultural identity); functional contribution (effects on durability, comfort, breathability, weather resistance, and ease of maintenance); production feasibility (labor intensity, scalability, reproducibility, and equipment requirements); material compatibility (suitability for various substrates such as leather, textiles, or synthetics); sustainability (environmental footprint, recyclability, toxicity, and alignment with circular production principles); and cultural or symbolic value (historical significance, social meaning, and ethical considerations such as cultural appropriation).

Table 1 summarizes the evaluation criteria for decorative techniques. The framework enables a structured comparison of techniques, highlighting inherent trade-offs—for example, hand embroidery offers high aesthetic and cultural value but scores low on durability and production feasibility, whereas water-based dyeing excels in sustainability and durability but yields more understated visual effects. By making these trade-offs explicit, the evaluation framework translates academic findings into actionable guidance for designers and manufacturers.

Table 1: Evaluation criteria for decorative techniques

| Criterion                 | Description                                                        | Example application                             |
|---------------------------|--------------------------------------------------------------------|-------------------------------------------------|
| Aesthetic impact          | Visual appeal, complexity, distinctiveness                         | Embroidery vs. simple dyeing                    |
| Functional contribution   | Effects on durability, comfort, breathability, weather resistance  | Protective coatings vs. purely ornamental beads |
| Production feasibility    | Cost, scalability, skill requirements                              | Laser engraving vs. hand embroidery             |
| Material compatibility    | Suitability for different substrates (leather, textile, synthetic) | Patina on leather vs. printing on mesh          |
| Sustainability            | Environmental footprint, recyclability, toxicity                   | Water-based dyes vs. solvent-based coatings     |
| Cultural / symbolic value | Historical or social meaning                                       | Lotus shoe embroidery vs. minimalist monogram   |



Having established a clear classification system—textures, ornaments, patterns, surface treatments, colors, and specialized effects—the next question is why these categories matter. Classification alone does not explain the functional, commercial, or psychological roles that decorative finishes play in footwear design. The following section therefore shifts from taxonomy to analysis, examining the significance of these finishes: how they shape brand identity, influence consumer preferences, and bridge aesthetics with wearability, comfort, and longevity.

## SIGNIFICANCE OF DECORATIVE FINISHES IN FOOTWEAR DESIGN

### Aesthetic Appeal and Brand Identity

Decorative finishes are essential in footwear design, blending artistry with

branding. These finishes transform shoes from mere functional items into fashion statements, helping brands communicate their identity and connect with consumers on an emotional and visual level. Whether through subtle embossing or bold embellishments, these details define a shoe's character and market positioning.

Decorative finishes play a crucial role in enhancing footwear by adding visual value and uniqueness, ultimately driving consumer attraction and satisfaction. These finishes elevate designs through various techniques such as metallic coatings, embossing, embroidery, and innovative surface textures, creating visually striking products. High-end treatments like gold foiling, patent leather sheens and crystal embellishments evoke a sense of luxury and premium craftsmanship, appealing to discerning buyers.



Figure 3. (a) Christian Louboutin leather lace-up shoes showing the iconic red soles [33], (b) Louis Vuitton black monogram embossed leather punchy high top sneakers [34], (c) Doc Martens' yellow stitching [35], (d) Prada's Downtown metallic leather sneakers [36], (e) Nike Air Force 1 Mid Off-White Graffiti White [37], (f) Pioneer's luminous smart shoes [38]

Additionally, decorative details enable customization and personalization [39], addressing growing consumer demand for distinctive, one-of-a-kind products. By incorporating seasonal trends—such as matte textures, glossy surfaces, or holographic effects—brands ensure their designs remain fashion-forward. Beyond aesthetics, textured finishes like suede, velvet, or embossed leather enhance sensory appeal, offering a

tactile experience that deepens the consumer's connection to the product.

Moreover, decorative finishes serve as powerful tools for brand differentiation and storytelling. Unique treatments allow brands to establish and maintain a recognizable identity in a competitive market. A prime example is Christian Louboutin's signature red soles (Figure 3a), which have become synonymous with the brand's exclusivity and prestige [40]. Through strategic use of

decorative elements, brands can communicate their heritage, values, and design philosophy, ultimately strengthening their market position and emotional resonance with consumers.

Other brand differentiation elements include signature design elements where specific finishes, such as monogram embossing (e.g., Louis Vuitton). Doc Martens' yellow stitching portrays a rugged, rebellious detail that has become synonymous with the brand's tough, countercultural ethos. Prada's minimalist metallic touches) set brands apart. These leather shoes stand out for the shiny gleam of the material.

Brands can use decorative finishes to reflect cultural influences or historical narratives, enriching their identity. Special decorative finishes in collaborations (e.g., Nike x Off-White's deconstructed aesthetic) enhance the brand's cultural relevance and market demand. Target Audience Appeal – Luxury brands use high-end finishes (e.g., patent leather, gold foil) to appeal to elite consumers, while streetwear brands may use bold graphics and graffiti-style prints. Figure 3e shows Nike Air Force 1 Mid Off-White Graffiti White. Therefore, the consistent use of distinctive finishes helps consumers easily recognize and trust a brand.

### **Role in Luxury and Designer Footwear**

Decorative finishes in luxury and designer footwear play a pivotal role in elevating shoes beyond mere functionality, transforming them into coveted works of art that reflect exclusivity, craftsmanship, and brand prestige. Luxury footwear often incorporates rare and high-quality materials that are inherently decorative and exclusive. Exotic leathers such as crocodile or ostrich, precious metals (Prada's Downtown metallic leather sneakers shown in Figure 3d), and gemstones not only enhance visual appeal but also signal rarity and sophistication.

These materials require specialized craftsmanship, adding to the exclusivity and cost of the final product. Bold patterns, unconventional textures, and avant-garde shapes are hallmarks of luxury footwear, reflecting the brand's identity and vision [40].

Limited-edition shoes with unique finishes—such as hand-painted designs or rare material combinations—appeal to collectors, often appreciating in value over time.

The tactile pleasure of supple leather, the visual delight of intricate beadwork, or the sound of a perfectly crafted heel all contribute to the allure. The significance of decorative finishes in luxury and designer footwear lies in their ability to convey exclusivity, craftsmanship, innovation, and brand prestige.

### **Consumer Preferences and Market Trends**

Decorative finishes serve as a crucial element in footwear design, directly influencing consumer choices and reflecting shifting market demands. As shoes function as wearable statements of personal identity [41], these aesthetic treatments become essential for expressing individuality, social standing, and functional requirements. Luxury finishes—whether artisanal stitching, supple leather grains or exotic materials—communicate prestige, catering to discerning buyers seeking distinction through craftsmanship and rarity.

The significance of decorative finishes in footwear design lies in their ability to fulfill consumer desires for self-expression [42], status, and functionality while keeping pace with market trends like sustainability, technology, and cultural diversity. Far from being mere embellishments, these finishes reflect the wearer's identity and the world they inhabit. For brands, understanding and leveraging these preferences and trends is crucial to crafting footwear that captivates modern consumers and thrives in a dynamic, ever-changing market.

Decorative finishes also mirror broader shifts in the footwear industry, driven by changing consumer values, technological innovation, and cultural influences. With growing environmental awareness, eco-friendly finishes are a major trend [43]. Recycled materials, organic fabrics, and plant-based dyes appeal to eco-conscious buyers. Brands like Adidas and Nike have embraced this shift, using finishes made from ocean

plastic or vegan leather to attract consumers who value sustainability alongside style.

The smart fashion revolution is transforming decorative finishes by integrating advanced technologies. Modern sneakers now feature illuminated LED accents (Figure 3f) for a sci-fi aesthetic, while intelligent textiles automatically adjust to body temperature for optimal comfort. The latest innovations include reactive coatings that shift hues in response to environmental changes – a cutting-edge feature that appeals to tech-savvy consumers eager to invest in groundbreaking footwear designs.

Decorative finishes in footwear design serve as a dynamic bridge between consumer aspirations and industry evolution. These aesthetic elements do more than follow trends—they actively shape the dialogue between personal identity and market forces. By blending self-expression with social signaling and practical performance, decorative treatments simultaneously address modern demands for eco-conscious materials, smart technology integration, and culturally inclusive design languages.

### **Influence of Social Media, Influencers, and Customization**

Decorative finishes in footwear design—such as unique colors, patterns, textures, or embellishments—have become increasingly significant in recent years due to the powerful interplay of social media, influencers, and the growing demand for customization. Together, these forces have transformed decorative finishes from mere aesthetic enhancements into critical elements that shape consumer preferences, enhance brand identity, and drive market trends.

Platforms such as Instagram, TikTok, and Pinterest have transformed footwear into a highly visual and shareable commodity, prioritizing striking aesthetics. Decorative elements like metallic finishes, vibrant gradients, or detailed embroidery can rapidly gain traction online, generating sudden surges in consumer interest. Including at least one hashtag in an Instagram post boosts its average reach [44]. Thus, users often tend to showcase their footwear using hashtags,

framing these designs as extensions of personal identity. This organic promotion amplifies the reach of unique aesthetics, positioning decorative details as central to digital engagement and brand visibility.

Influencers, spanning celebrities to micro-influencers, wield substantial power in shaping footwear trends by spotlighting decorative elements that appeal to their audience [45]. When they feature shoes with striking finishes—such as holographic details or artisanal embroidery—it ignites a desire among followers to replicate these styles. This aspirational dynamic can propel niche aesthetics into mainstream popularity. By curating products that align with their personal brand, influencers foster trust; consistently endorsing bold or artistic designs encourages audiences to adopt these trends, ultimately driving higher demand.

The rise of customization has redefined decorative finishes as a means of personal expression, allowing consumers to tailor footwear to their individual tastes. Platforms like Nike By Yo [46] or Adidas' miadidas [47] let customers select colors, patterns, and materials, turning decorative finishes into a creative outlet. A consumer might choose a vibrant colourway, add personalized embroidery, or pick a textured finish to craft a design that feels uniquely theirs.

Brands encourage customers to share their custom creations online in some cases using brand communities [48], create a cycle of inspiration and visibility. This organic sharing triggers powerful network effects—a single viral post of artisan-crafted sneakers can ignite global demand for similar personalized designs. The digital age has fundamentally redefined decorative finishes' role: social platforms provide the spotlight, influencers curate the trends, and bespoke customization delivers the emotional connection. Together, they've transformed surface treatments from passive ornamentation into active brand-building tools that drive engagement, enable self-narrative, and foster authentic community connections in today's experience-driven market.

### Impact of Footwear Decorative Finishes on Wearability, Comfort, and Longevity

In footwear design, decorative finishes serve purposes beyond aesthetics, directly influencing comfort, durability, and functionality. Techniques like textured embossing, precision laser etching, or reflective treatments are often applied to flexible materials to ensure they retain their adaptive properties. Opting for lightweight, flexible finishes ensures that ornamental details do not hinder mobility, prioritizing wearer comfort. Increasingly, decorative elements are engineered for dual purposes [49]. For instance, water-repellent coatings that combine a polished aesthetic with weather resistance enhance practicality, allowing shoes to perform in diverse climates while preserving their visual appeal.

Finishes that incorporate perforations or use breathable materials can help regulate temperature and moisture. This enhances comfort by preventing excessive heat buildup or dampness, which can lead to discomfort during prolonged wear [50]. Many decorative finishes include protective elements, such as UV-resistant or anti-abrasion coatings, that help maintain the shoe's appearance and structural integrity over time. These finishes can guard against environmental factors like sunlight, moisture, and dirt, thereby extending the shoe's lifespan.

Decorative finishes are integral to modern footwear design, serving a dual purpose: they enhance the visual appeal and contribute to functional aspects such as wearability, comfort, and durability. By carefully selecting and integrating these finishes, designers can create products that not only capture consumer attention but also deliver superior performance and longevity. This thoughtful balance between form and function is a hallmark of successful footwear brands, where every design detail—from the sheen on a patent leather accent to the texture of a breathable knit upper—is optimized for both style and practicality.

### Factors Influencing the Choice of Decorative Finishes Across Historical Periods

Across different eras and civilizations, the selection of decorative finishes for footwear has never been arbitrary. Rather, it has been shaped by a recurring set of social, technological, and environmental forces. This subsection identifies and analyzes seven persistent factors—social hierarchy, religious or symbolic beliefs, material availability and craftsmanship, economic conditions, technological breakthroughs, cultural exchange and globalization, gender norms and their contemporary parallel have been summarized in Table 2.

Table 2: Factors influencing the choice of decorative finishes across historical periods

| Factor                                | Historical example                                                            | Contemporary parallel                                       |
|---------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------|
| Social hierarchy / status             | Chinese imperial regulations on shoe styles; poulaines in medieval Europe     | Luxury brand signature finishes (e.g., Louboutin red soles) |
| Religious / symbolic beliefs          | Sacred iconography on medieval European footwear                              | Cultural motifs in modern customization                     |
| Available materials and craftsmanship | Silk embroidery in Tang Dynasty; hand-tooled leather in Renaissance           | Vegan leathers, 3D-printed components                       |
| Economic conditions                   | Simpler designs during wartime vs. opulence in prosperous eras                | Cost constraints vs. premium customization today            |
| Technological breakthroughs           | Industrial Revolution mechanization; laser cutting                            | 3D knitting, digital printing, AR                           |
| Cultural exchange / globalization     | Chinese and Pacific influences on 19 <sup>th</sup> -century European footwear | Cross-cultural trends amplified by social media             |
| Gender norms and ideals               | Lotus shoes (bound feet) in China; heel heights in Europe                     | Unisex designs, gender-fluid finishes                       |

Understanding the significance of decorative finishes—as tools for branding, luxury signaling, and consumer engagement—sets the stage for examining where the

industry is heading. The landscape of footwear decoration is not static; it is rapidly evolving under pressure from environmental concerns, technological breakthroughs, and shifting



consumer desires for personalization. The next section surveys the most prominent contemporary trends, including sustainable materials, digital fabrication techniques, and the tension between minimalist and extravagant design philosophies.

## CURRENT TRENDS IN FOOTWEAR DECORATIVE FINISHES

### Sustainability and Eco-Friendly Materials

The use of sustainable and eco-friendly materials in decorative finishes for footwear has emerged as a prominent trend in recent years, reflecting broader shifts in consumer preferences and industry practices toward environmental responsibility and ethical production. This trend is driven by growing awareness of the environmental impact of traditional footwear manufacturing, which often relies on resource-intensive processes and synthetic materials derived from fossil fuels. As a result, designers and brands are increasingly incorporating sustainable materials into decorative finishes—elements like trims, embellishments, coatings, and surface treatments—to enhance aesthetics while reducing ecological harm.

One key aspect of this trend is the adoption of recycled materials for decorative finishes. For instance, brands are using recycled plastics, such as polyester from post-consumer plastic bottles, to create glossy or textured coatings that serve as stylish finishes. Companies like Adidas have embraced this approach, notably through their partnership with Parley for the Oceans (Figure 4a, Parley X Adidas 4DFWD running shoes made recycled ocean plastics), where intercepted ocean

plastic is transformed into recycled polyester yarns used not only for shoe uppers but also for decorative elements like stitching and overlays.

Another sustainable material gaining traction is plant-based leather alternatives, such as those made from pineapple leaves [51] (Piñatex) [52], mushrooms, or cork, which are being used for decorative accents like embossed patterns or laser-cut designs. For example, Veja, a leading sustainable footwear brand, integrates bio-based leather and organic cotton into its sneakers [53], often featuring minimalist yet elegant finishes that appeal to eco-conscious consumers. These materials offer unique textures and natural hues, reducing reliance on traditional leather—whose production contributes to deforestation and greenhouse gas emissions—and providing a cruelty-free aesthetic appeal. A Future Market Insights report notes that such innovations in material science are a major selling point, differentiating brands in a competitive market.

Additionally, biodegradable finishes are emerging as a cutting-edge trend. Water-based coatings and dyes, which avoid harmful solvents and chemicals, are being applied to footwear to achieve vibrant or matte decorative effects. Nike's waterless dye technology, for instance, saves energy and eliminates chemical additives in fabric dyeing, offering a sustainable way to produce visually striking finishes. This approach not only lowers the carbon footprint but also ensures that the footwear decomposes more naturally at the end of its lifecycle.



Figure 4. (a) Parley X Adidas 4DFWD running shoes [54], (b) New Balance's newest sustainable kicks are created from leftover surplus material [55]

The movement toward eco-conscious design now includes natural and upcycled materials for decorative elements. As illustrated in Figure 4b, New Balance's latest sustainable sneakers are crafted from surplus materials, specifically recycled production scraps from the brand's existing product lines. These vibrant shoes exemplify how waste materials can be transformed into bold, eye-catching footwear while aligning with circular fashion principles.

Ethiopian brand soleRebels, for example, uses hand-loomed fabrics from organic cotton and recycled tire rubber soles, often adorned with colorful woven accents that serve as decorative highlights [56, 57]. Similarly, rice husk—a byproduct typically discarded in landfills—is being processed by footwear company Suggies and combined with natural rubber to create durable, eco-friendly outsoles with a distinctive speckled finish [58].

These finishes add visual interest while reducing waste and fossil fuel dependency. Consumer demand is a significant driver

behind this shift [59]. This demand has pushed brands to prioritize transparency and eco-labels, such as GOTS or Bluesign [60], which certify the sustainability of materials used in finishes.

In succinct, the use of sustainable and eco-friendly materials in decorative finishes for footwear reflects a fusion of style and sustainability, leveraging recycled plastics, plant-based alternatives, biodegradable coatings, and upcycled natural materials. References from industry leaders like Adidas, Veja, and Nike, underscore this trend's momentum, highlighting its role in reshaping footwear design for a greener future.

### Technology-Driven Innovations in Footwear Decorations

The imperative to streamline production timelines, lower expenses, conserve materials, and improve waste handling is driving widespread implementation of innovative manufacturing techniques [61].

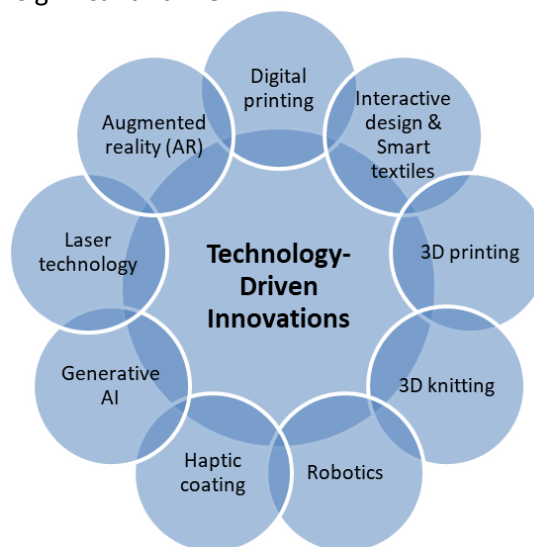


Figure 5. Examples of Technology-Driven Innovations in footwear decoration

Cutting-edge technologies and parametric design methodologies enable enhanced production of complex geometries, customized products, and personalized footwear solutions [62]. Figure 5 presents examples of these technological advancements applied in decorative footwear design. 3D printing has revolutionized footwear customization, allowing designs with

unprecedented complexity—from ultra-lightweight frames to intricate detailing—that traditional manufacturing cannot replicate [63]. Brands like Reebok showcase this potential with innovations such as their 'Liquid Speed' sneaker, featuring a high-performance, 3D-printed outsole with striking aesthetic appeal [64].

Footwear customization leverages advanced digital techniques like inkjet printing – including Direct-to-Film (DTF) and pre-treated fabric methods – enabling vibrant personalized designs on canvas shoes. Similarly, digital embroidery merges artisanal quality with precision technology, producing durable, intricate patterns ideal for brand logos and fashion accents across sneakers and boots [65].

Interactive designs and smart textiles for footwear decoration incorporate elements that respond to user interaction, environmental changes, or technology, creating a dynamic and engaging experience. These designs merge fashion with functionality, making shoes more than just wearable—they become expressive, adaptive, or even playful. Examples include interactive dance shoes and with the ability to capture high-level podiatric gestures [66].

There are also color-changing & thermochromic applications, LED & Light-up footwear, and the use of pressure sensors (e.g., piezoelectric materials) to trigger visual changes. Self-cleaning and hydrophobic coating applications, Embedded NFC chips link to digital content (ownership verification, exclusive access). Others include self-lacing [67], microencapsulated fragrances that release scent when rubbed or heated and biometric feedback integration applications.

Interactive footwear and smart textiles are pushing the boundaries of fashion, function, and tech. Whether through color-shifting fabrics, self-lacing systems, or AR-enhanced sneakers, the future of shoes is adaptive, connected, and sustainable.

Laser technology is redefining footwear design by replacing manual, time-intensive methods with innovative solutions that expand creative potential [68]. This approach alters material surfaces—for instance, imparting a weathered or vintage appearance to leather or creating reflective or metallic finishes on footwear without requiring additional materials. Through precise thermal control, lasers produce distinctive effects such as burnishing, texturing, or color shifts, enhancing both visual depth and aesthetic value in shoe design.

Innovations like 3D knitting are transforming the footwear sector by delivering tailored, seamless decorative elements that boost both comfort and functionality. This method enables the direct integration of detailed, complex patterns into the shoe's framework, producing lighter, more breathable, and eco-friendly footwear. By minimizing material waste, 3D knitting aligns with the increasing consumer demand for bespoke solutions that prioritize sustainability and individuality [62].

The integration of robotics is revolutionizing footwear decoration. In a study by Borrell *et al.*, a robotic polishing system was developed to expedite the development of patina on premium leather shoes. This automated technology streamlines the polishing process, reducing labor time while ensuring consistent, high-quality finishes [69].

Haptic coatings involve the use of highly elastic, soft-touch materials applied to products such as footwear, toys, furniture, and automotive interiors, designed to deliver a distinctive tactile effects on surfaces [70]. Initially developed by China's Fujian Huafeng New Materials Co., Ltd. and BASF Coatings GmbH, these coatings are now leveraged in footwear customization through digital printing, enabling stylish textured finishes and personalized designs that merge sensory appeal with aesthetic individuality [71].

Generative AI (GenAI / GAI) is a form of artificial intelligence designed to produce original content such as text, images, videos, and music. It utilizes machine learning models to analyze data and create new outputs. By leveraging training data, GAI generates fresh text, images, or audio. Notable examples include GPT-4 and Midjourney, which are widely used and have significantly influenced work and communication practices [72]. Footwear design and decoration is also benefiting from this new technology. Using a text-to-image GAI tool called Midjourney, [73] experimented with 17 prompts to create footwear concepts.

Augmented Reality (AR) is defined as a real-time, direct or indirect view of the physical world that is enhanced by

incorporating virtual, computer-generated information [74]. Augmented reality has also found application in footwear decoration. AR affords consumers the chance to specify various footwear design attributes including color, texture, embroidery, and shape for personal customization [75].

### Minimalist vs. Extravagant Designs

Contemporary footwear design exhibits two divergent philosophical approaches: minimalist and maximalist constructions. Minimalist footwear is also interpreted in two distinct ways. The first perspective defines it as footwear engineered to mimic the barefoot experience while providing essential protection and insulation, particularly in the

sole. Such designs are commonly labeled as “minimalist.” [64].

Examples include footwear with lower heels, minimal or devoid of cushioning, more pliable soles, and without inherent arch support minimalist running shoes [76]. Figure 6(a) presents Vibram Five Fingers minimalist or barefoot shoe. The second interpretation characterizes minimalist footwear by its emphasis on restrained ornamentation, where design elements prioritize sophistication, utility, and clean aesthetics. In this approach, decorative details remain subtle – acting as complementary enhancements rather than focal points – while showcasing premium materials and artisanal construction, an example is shown in Figure 6c.



Figure 6. (a) Vibram Five Fingers minimalist or barefoot shoe [77], (b) Footwear with inflated soles, (c) Men's minimalist sneaker, (d) Footwear with excessive decorations [78]

In direct contrast to first minimalist approach, maximalist footwear approaches features substantially amplified midsoles [79, 80] designed to provide superior cushioning and enhanced impact dispersion relative to conventional running shoes. The second maximalist approach features maximalism or extravagant designs embracing grandeur, celebrating excess and self-expression. Figure 6d is an example of footwear with excessive decorations. The evolutions of fashion and

shifts in consumer priorities have led to the emergence of these opposing currents dominating footwear decoration.

### Customization and Personalization

Product customization centers on integrating individual customer preferences into the design of new offerings, directly involving customers in the creation process to improve their satisfaction [81]. In footwear, personalization through decorative elements



enables individuals to adapt their shoes to express their distinct tastes, style, and personality. By treating standard shoes as a platform for artistic innovation, this practice merges practical utility with self-expression, allowing wearers to infuse their identity into everyday items.

Custom footwear options include monogrammed initials, names, or symbolic designs through engraving, embroidery, or printing. Consumers can select unique color palettes or collaborate with designers for artistic finishes. Functional adaptations like modular soles, interchangeable uppers, and tailored insoles merge style with practicality. Heritage-inspired decorations – from cultural motifs to family crests – celebrate personal

narratives. The growing market of DIY kits and made-to-order solutions transforms shoes into wearable self-expression, combining craftsmanship, innovation, and identity through decorative detailing.

To help designers balance customization demands with practical constraints, Table 3 compares eight decorative techniques across aesthetic impact, durability, and sustainability (rated High/Medium/Low), with a fourth column for best use cases. Highlighting trade-offs between visual appeal, longevity, and environmental responsibility, the table offers actionable guidance for design decision-making.

Table 3: Comparative analysis of decorative techniques by evaluation criteria

| Decorative technique             | Aesthetic impact | Durability | Sustainability | Best use case                    |
|----------------------------------|------------------|------------|----------------|----------------------------------|
| Hand embroidery                  | High             | Low        | Medium         | Luxury / cultural collections    |
| Laser engraving                  | Medium-High      | Medium     | Medium         | Brand logos, textured surfaces   |
| 3D printed ornaments             | High             | Low-Medium | Low            | Limited editions, runway pieces  |
| Beading / rhinestones            | High             | Low        | Low            | Evening / event shoes            |
| Water-based dyeing               | Medium           | High       | High           | Everyday footwear, outdoor shoes |
| Patina (hand-rubbed)             | High             | Medium     | Medium         | Premium / heritage footwear      |
| Digital embroidery               | Medium-High      | High       | Medium         | Sports apparel, high-wear areas  |
| Holographic / iridescent coating | High             | Low        | Low            | Trend-driven / statement pieces  |

Figure 7 presents a decision flow diagram that guides footwear designers through a series of practical questions—starting with intended use, then prioritizing durability, aesthetics, or sustainability. Following the diagram leads to recommended decorative techniques tailored to each design context, translating the study’s comparative findings into an easy-to-follow visual tool.

The trends discussed above—from 3D-printed customization to eco-friendly coatings—demonstrate the footwear

industry’s capacity for innovation. However, each trend also brings unresolved tensions: sustainability claims may mask greenwashing, smart textiles raise durability and regulatory questions, and personalization drives up production costs. The following section confronts these challenges directly, while also looking ahead to emerging possibilities such as generative AI, self-healing materials, and augmented reality interfaces that may redefine decorative finishes in the coming decade.

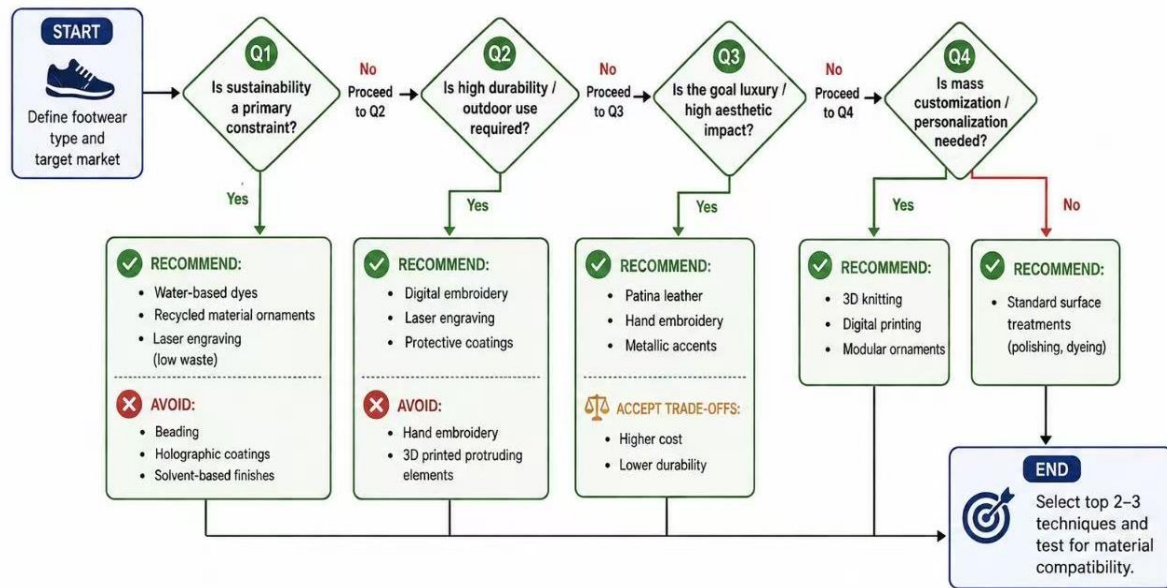


Figure 7. Decision flow diagram for selecting decorative finishes

## CHALLENGES AND FUTURE CONSIDERATIONS

Footwear design and production must carefully harmonize visual appeal with practicality. While eco-friendly materials can restrict finishing choices, advanced manufacturing techniques often come at a higher price. Companies need to carefully manage these compromises to satisfy consumer demands for both fashionable and ethically made products. Contemporary fashion brands face increasing demands to demonstrate genuine environmental responsibility. However, as sustainability claims come under greater examination, some companies resort to greenwashing – the practice of exaggerating or fabricating eco-friendly credentials without substantive evidence or meaningful action [82, 83].

Integrating advanced technology into footwear design offers innovative potential, but widespread use faces major challenges. Shoes undergo constant stress—friction, moisture, and bending—which can damage sensitive electronics and smart materials. For instance, embedded LEDs or sensors may fracture under repeated flexing, while thermochromic coatings can degrade after washing or sun exposure. Similarly, conductive threads may wear out or break over time due to strain or laundering.

Smart footwear features like LEDs, haptic feedback, and AR integration demand reliable power sources, yet batteries increase weight and require frequent charging. Renewable options like solar or kinetic energy often fail to meet the demands of power-intensive functions. Overly intricate designs could also compromise usability—for example, AR-enabled shoes may depend on uninterrupted internet access. Additionally, technology-laden footwear risks generating significant e-waste through non-recyclable components and hazardous materials.

Smart footwear incorporating technology may encounter stringent regulatory hurdles, including FCC/CE (Federal Communications Commission)/ (Conformité Européenne) and certifications for wireless components and safety standards for conductive materials. Existing aviation restrictions on lithium batteries could also pose challenges—most airlines currently limit passengers to carrying two to five spare batteries under 100 watt-hours each, while banning those exceeding 160 watt-hours. These regulations may complicate the transportation of tech-enabled shoes, particularly those with built-in power sources.

For the future however, it is undeniable that the footwear industry is undergoing a dramatic transformation, where the future of decorative design lies at the intersection of

art, technology, and sustainability. Imagine shoes with self-repairing surfaces that erase scuffs, nano-engineered materials that adapt their color like chameleons, or bio-fabricated pigments that shift hues sustainably. Tomorrow's footwear could sync with your devices, respond to emotions by altering colors based on mood, or even pulse with your heartbeat. Meanwhile, generative AI might empower wearers to craft unique, algorithmically generated designs for 3D-printed customization. These innovations promise to redefine not just style, but the very relationship between shoes and their wearers.

Balancing aesthetic ambition with practical constraints—and navigating ethical, environmental, and technological hurdles—remains the central task for footwear designers and manufacturers. Having analyzed both the persistent challenges and the promising future directions, we now synthesize the paper's core findings. The conclusion revisits the historical, classificatory, and trend-based insights presented above, ultimately arguing that decorative finishes occupy a unique intersection of art, identity, and engineering—one that will continue to shape footwear design for years to come.

## CONCLUSION

Decorative finishes in footwear design represent a dynamic confluence of tradition, innovation, and cultural expression, serving as both functional enhancements and powerful markers of identity. Historically rooted in socio-cultural practices—from the symbolic lotus shoes of imperial China to the opulent designs of Renaissance Europe—these finishes have evolved to reflect technological advancements and shifting consumer values. Today, they play a pivotal role in bridging aesthetic appeal with practical performance, while addressing contemporary demands for sustainability and personalization.

The study underscores the transformative impact of current trends, particularly the adoption of eco-friendly materials (e.g., recycled plastics, plant-based leathers) and cutting-edge technologies such as 3D printing, laser engraving, and smart

textiles. These innovations not only reduce environmental footprints but also enable unprecedented customization, allowing consumers to imprint their individuality onto footwear. Social media and influencers further amplify trends, turning niche designs into global phenomena through viral visibility and aspirational branding.

From a practical standpoint, this study offers three key contributions for industry professionals. First, the proposed six-category classification system provides designers and manufacturers with a shared vocabulary and a structured framework for exploring decorative options. Second, the evaluation criteria—*aesthetic impact, durability, and sustainability*—establish a reusable template for comparing finishing techniques before prototyping, enabling more deliberate trade-off management.

Third, the historical and contemporary factor analysis reveals that choices in decorative finishes have consistently been shaped by social, technological, and environmental forces; brands can leverage this insight when positioning products or developing signature finishes. Collectively, these findings translate into actionable guidance: no single decorative technique excels across all criteria, and optimal selection depends on balancing visual ambition with functional demands and ethical responsibility, tailored to the intended use and target market.

## REFERENCES

1. Boas, G., *The Esthetics of the Middle Ages* by Edgar de Bruyne, Eileen B. Hennessy, *J Aesthet Art Crit*, **1970**, 29, 1, 131-2, <https://doi.org/10.2307/428820>.
2. Buckle, N., *The Evolution of Aesthetics: A Retrospective on 20th Century Design*, Medium, December 22, 2023, available from: <https://medium.com/@nicolecarlabuckle/the-evolution-of-aesthetics-a-retrospective-on-predominantly-20th-century-design-a6630379f14e>.
3. Khan, S.I., *Fashion Design Mastery: Trends, Techniques, and Creative Insights*, Libertatem Media Private Limited, **2023**.
4. Chatterjee, K.N., Jhanji, Y., Grover, T., Bansal, N., Bhattacharyya, S., 6 - Selecting Garment

- Accessories, Trims, and Closures, in: Nayak, R., Padhye, R. (eds.), *Garment Manufacturing Technology*, Woodhead Publishing, **2015**, pp. 129-84, <https://doi.org/10.1016/B978-1-78242-232-7.00006-0>.
5. Laiwechpittaya, T., Udomkit, N., A Matter of Shoes: The Analysis of Desired Attributes of Shoes and Its Retail Shops from Bangkok Consumers' Perspectives, *Int J Mark Stud*, **2012**, 5, 2, 33-40, <https://doi.org/10.5539/ijms.v5n2p33>.
  6. Zujie, Y., Dressing for Power: Rite, Costume, and State Authority in Ming Dynasty China, *Frontiers of History in China*, **2007**, 2, 2, 181-212, <https://doi.org/10.1007/s11462-007-0012-x>.
  7. Ning, L., Literature in the Late Years of the Tang Dynasty and the Five Dynasties, in Liu, Y. (ed.), *Concise Reader of Chinese Literature History*, Springer, **2023**, p. 237-59, [https://doi.org/10.1007/978-981-99-5814-6\\_18](https://doi.org/10.1007/978-981-99-5814-6_18).
  8. Jiaqin, Z., Liang, H., Porcelain-made Lotus Shoes in the Qing Dynasty of China, *Ceramics: Art and Perception*, **2018**, 110, 80-5.
  9. Maheshwari, A., Most Beautiful Traditional Footwear From Around The World, **2022** [accessed 2025], available from: <https://yodoozy.com/most-beautiful-traditional-footwear-from-around-the-world/>.
  10. Cao, Z., Yuan, G., Sheng, R., Liu, S., The Influence of Chinese Cultural Elements in Footwear Design, *Textile Science and Economy*, **2022**, 10, 88-94.
  11. Bland, E., Chinese Lotus Shoes: Museum of Anthropology, University of Missouri, **2022**, available from: <https://anthromuseum.missouri.edu/exhibits/chinese-lotus-shoes>.
  12. What kind of shoes did ancient Chinese people wear? Fashion Hanfu, September 8, **2020**, available from: <https://www.fashionhanfu.com/shoes-chinese-for-ancient-people/>.
  13. Liao, F., Apirating, P., Kotchapakdee, P., Buarabha, H., Meishan Scroll Paintings and Ancestor Worship of the Flat Land Yao People in Gongcheng Yao Autonomous District, Guangxi Zhuang Autonomous Region, China, *Asian Ethn*, **2022**, 23, 3, 541-55, <https://doi.org/10.1080/14631369.2021.2021795>.
  14. Martínez-Sevilla, F., Herrero-Otal, M., Martín-Seijo, M., Santana, J., Lozano Rodríguez, J.A., Maicas Ramos, R., et al., The Earliest Basketry in Southern Europe: Hunter-gatherer and Farmer Plant-based Technology in Cueva de los Murciélagos (Albuñol), *Sci Adv*, **2023**, 9, 39, eadi3055, <https://doi.org/10.1126/sciadv.adi3055>.
  15. Mark, J.J., Fashion & Dress in Ancient Egypt, **2017** [accessed 2024], available from: <https://www.worldhistory.org/article/1037/fashion-dress-in-ancient-egypt/>.
  16. Wilcox, R.T., *The Mode in Footwear: A Historical Survey with 53 Plates*, Courier Corporation, **2008**.
  17. Peck, W.H., *The Material World of Ancient Egypt*, Cambridge University Press, **2013**, <https://doi.org/10.1017/CBO9781139034296>.
  18. McCormack, M., 'So Manly and Ornamental': Shoe Buckles and Britain's Eighteenth Century, *Engl Hist Rev*, **2023**, 138, 592, 474-96, <https://doi.org/10.1093/ehr/cead102>.
  19. Tammen, J.A., Historical Tracing of American Women's Shoes from Colonial Days with Identification Criteria for the Years 1890 to 1930, Master's Thesis, Oklahoma State University, **1973**.
  20. Kutnjak-Mravlinčić, S., Akalović, J., Bischof, S., Merging Footwear Design and Functionality, *Autex Res J*, **2019**, 20, 4, 372-81, <https://doi.org/10.2478/aut-2019-0023>.
  21. Bensmaia, S., Texture from Touch, Scholarpedia: scholarpedia.org, **2009**, p. 7956, <https://doi.org/10.4249/scholarpedia.7956>.
  22. Thieulin, C., Paillet-Mattei, C., Vargiolu, R., Lancelot, S., Zahouani, H., Study of the Tactile Perception of Bathroom Tissues: Comparison Between the Sensory Evaluation by a Handfeel Panel and a Tribo-acoustic Artificial Finger, *Colloids Surf B Biointerfaces*, **2017**, 150, 417-25, <https://doi.org/10.1016/j.colsurfb.2016.11.006>.
  23. Luible, C., Varheenmaa, M., Magnenat-Thalmann, N., Meinander H, Subjective Fabric Evaluation, 2007 International Conference on Cyberworlds (CW'07), 24-26 Oct. **2007**, Hannover, Germany, IEEE, <https://doi.org/10.1109/CW.2007.57>.
  24. Malcoci, M., Pascari, I., Contributions to Classification Zippers Used in Industry Footwear and Leather Goods, *Ann Univ Oradea, Fasc Textile Leatherwork*, **2016**, 1, 175-8.
  25. Sok, A., Your Art Path, 15 December, **2023** [accessed 2025], available from: <https://yourartpath.com/what-is-pattern-principle-in-art#:~:text=Patterns%20in%20art%20refer%20%E%80%80to%20the%20repetition>.
  26. Liu, Y., Toussaint, G.T., The Marble Frieze Patterns of the Cathedral of Siena: Geometric Structure, Multi-stable Perception and Types of Repetition, *J Math Arts*, **2011**, 5, 115-27, <https://doi.org/10.1080/17513472.2011.551933>.
  27. Arnold, J., Decorative Features: Pinking, Snipping and Slashing, *Costume*, **1975**, 9, 1, 22-6, <https://doi.org/10.1179/cos.1975.9.1.22>.
  28. Qiu, X., Li, J., Qi, D., One-step Coating for Simultaneous Functionalization and Pigment



- Colored of Synthetic Leather, *Colloids Surf A: Physicochem Eng Asp*, **2025**, 710, 136207, <https://doi.org/10.1016/j.colsurfa.2025.136207>.
29. Reddy, S.M., Chowdhury, A., Chakrabarti, D., Karmakar, S., Role of Colour and Form in Product Choice and Variation of Preferences Across Product Categories: A Review, in Chakrabarti, A. (ed.), *ICoRD'15 – Research into Design Across Boundaries Volume 2*, **2015**, New Delhi: Springer India, [https://doi.org/10.1007/978-81-322-2229-3\\_54](https://doi.org/10.1007/978-81-322-2229-3_54).
  30. Kinuthia, L.N., Keren, G., Burugu, M., Muthomi, H., Mwihaki, M., Factors Influencing Brand Loyalty in Sportswear among Kenyan University Students: The Case of Swimmers, *Differences*, **2012**, 1, 4, 223-231.
  31. Xu, D.-D., Wu, C.-F., Wang, C.-S., A Study on Perception of Visual-Tactile and Color-Texture Features of Footwear Leather for Symmetric Shoes, *Symmetry*, **2023**, 15, 7, 1462, <https://doi.org/10.3390/sym15071462>.
  32. Bove, Jr., V.M., Reader, N.A., Holography and the Luxury Industry, *Photonics*, **2021**, 8, 6, 219, <https://doi.org/10.3390/photonics8060219>.
  33. Christian Louboutin - Men's Our Georges leather lace-up shoes [accessed 2025], available from [https://www.beyondstyle.us/prod/christian-louboutin-our-georges-leather-laceup-shoes?id=mytheresa\\_P00632388](https://www.beyondstyle.us/prod/christian-louboutin-our-georges-leather-laceup-shoes?id=mytheresa_P00632388).
  34. Louis Vuitton Black Monogram Embossed Leather Punchy High Top Sneakers, The Luxury Closet, **2025** [accessed 2025], available from: <https://theluxurycloset.com/women/louis-vuitton-black-monogram-embossed-leather-punchy-high-top-sneakers-size-385-p87075>.
  35. Lane, V., New Launch: Dr. Martens Double Stitch pack, The Garnette Report, **2020** [accessed 2025], available from: <https://thegarnettereport.com/fashion/new-launch-dr-martens-double-stitch-pack/>.
  36. Downtown Metallic Leather Sneakers, Border Gara, **2024**, available from: <https://bordergara.com/products/pr-2306-0285>.
  37. Kanesa, D., Sleek Graffiti-Adorned Sneakers, Trendhunter, 2022 [accessed 2025], available from: <https://www.trendhunter.com/trends/graffiti-1>.
  38. Wearable Battery Helps Smart Shoes Lead the Future, Grepow, 18 April **2019** [accessed 2025], available from: <https://www.grepow.com/blog/wearable-battery-helps-smart-shoes-lead-the-future.html>.
  39. Shang, X., Shen, Z., Xiong, G., Wang, F.-Y., Liu, S., Nyberg, T.R., Wu, H., Guo, C., Moving from Mass Customization to Social Manufacturing: A Footwear Industry Case Study, *Int J Comput Integr Manuf*, **2019**, 32, 2, 194-205, <https://doi.org/10.1080/0951192X.2018.1550675>.
  40. Gilroy, D.-J., *Little Book of Christian Louboutin: The Story of the Iconic Shoe Designer*, Hachette UK, **2021**.
  41. Braithwaite, N., These Shoes Were Made for Talking: Documenting Identity through the Lens of Footwear, *International Journal of the Image*, **2021**, 12, 2, 45-64, <https://doi.org/10.18848/2154-8560/CGP/v12i02/45-64>.
  42. Goodacre, L.J., Candy, F.J., 'If I Didn't Have RA I Wouldn't Give Them House Room': The Relationship Between RA, Footwear and Clothing Choices, *Rheumatology*, **2011**, 50, 3, 513-7, <https://doi.org/10.1093/rheumatology/keq347>.
  43. Asabuwa Ngwabebhoh, F., Saha, N., Saha, T., Saha, P., Bio-innovation of New-generation Nonwoven Natural Fibrous Materials for the Footwear Industry: Current State-of-the-Art and Sustainability Panorama, *J Nat Fibers*, **2022**, 19, 13, 4897-907, <https://doi.org/10.1080/15440478.2020.1870635>.
  44. Erz, A., Marder, B., Osadchaya, E., Hashtags: Motivational Drivers, Their Use, and Differences Between Influencers and Followers, *Computers in Human Behavior*, **2018**, 89, 48-60, <https://doi.org/10.1016/j.chb.2018.07.030>.
  45. Gupta, V.P., Sharief, S., Rani, S., Digital fashion and social media influencer in industry 5.0., in Raj, P., Rocha, A., Dutta, P.K., Fiorini, M., Prakash, C. (eds.), *Illustrating Digital Innovations Towards Intelligent Fashion*, Springer, **2024**, pp. 125-47, [https://doi.org/10.1007/978-3-031-71052-0\\_4](https://doi.org/10.1007/978-3-031-71052-0_4).
  46. Standaert, W., Product Digitalization at Nike: The Future is Now, *J Inf Technol Teach Cases*, **2022**, 12, 1, 28-34, <https://doi.org/10.1177/2043886920963286>.
  47. Piller, F.T., Lindgens, E., Steiner, F., Mass Customization at Adidas: Three Strategic Capabilities to Implement Mass Customization, **2012**, 1994981, available from SSRN, <https://doi.org/10.2139/ssrn.1994981>.
  48. Müller, D., The Role of Brand Communities within the Athletic Footwear Industry, Bachelor's Thesis, Zurich University of Applied Science, **2017**.
  49. Luximon, A., Khandual, A., Footwear, in Williams, J. (ed.), *Waterproof and Water Repellent Textiles and Clothing*, Elsevier, **2018**, pp. 533-58, <https://doi.org/10.1016/B978-0-08-101212-3.00017-4>.
  50. Kanjana, S., Nalankilli, G., Smart, Waterproof, Breathable Sportswear - A Review, *J Text Appar Technol Manag*, **2018**, 10, 3.

51. Gao, X., Wearing Pineapple Leaves? Consumer Responses to Fashion Products Made from Repurposed Materials, PhD Thesis, Wageningen University and Research, **2023**.
52. Kinnunen, S., All-Cellulose Shoe: Novel Wood-Based Materials in Footwear, Bachelor's Thesis, Häme University of Applied Sciences, **2017**.
53. Silvestre Zottin, L., The Environmental Performance of Footwear in an Eco-friendly company and Recommendations to Increase Sustainable Value Creation, Master's Thesis, Utrecht University, **2019**.
54. Grimes, C., Parley x Adidas Push Sustainability "4DFWD" with New Footwear, Hypebae, **2023**, available from: <https://hypebae.com/2023/2/parley-adidas-4dfwd-running-shoes-sneakers-release-info-where-to-buy-price-info>.
55. Mitra, S., New Balance's Newest Sustainable Kicks Are Created from Leftover Surplus Material, Yanko Design, **2020** [accessed 2025], available from: <https://www.yankodesign.com/2020/02/27/new-balances-newest-sustainable-kicks-are-created-from-leftover-surplus-material/>.
56. Alehegn, T., soleRebels: Eco Ethical Fashion from Ethiopia, Tadias, **2009** [accessed 2025], available from: <http://www.tadias.com/05/19/2009/solerebels-eco-ethical-fashion-from-ethiopia/>.
57. McCarthy, B., soleRebels – Targeting the Ethical Consumer, London: SAGE Publications, SAGE Business Cases Originals, **2016**, <https://doi.org/10.4135/9781473937499>.
58. Suggies - Sustainable Shoe Guide, **2025** [accessed 2025], available from: <https://www.shopsuggies.com/pages/suggies-sustainable-shoe-guide>.
59. Mittal, S., Khan, M.A., Yadav, V., Sharma, M.K., Footwear as Product-Service Systems: Toward Sustainable Alternative Consumption Scenarios, *Bus Strategy Environ*, **2024**, 33, 2, 726-41, <https://doi.org/10.1002/bse.3519>.
60. Marchi, A., Environmental Sustainability Certifications in the Fashion Industry, Master's Thesis, Ca' Foscari University of Venice, **2022**.
61. Pantazi-Băjenaru, M., Foiași, T., Gurău, D., Compositional Solutions and Assimilation of New Technical Elements with Applications of Design in Footwear Manufacturing, *Leather and Footwear Journal*, **2024**, 24, 3, 205-14, <https://doi.org/10.24264/lfj.24.3.3>.
62. Firtikiadis, L., Manavis, A., Kyratsis, P., Efklidis, N., Product Design Trends within the Footwear Industry: A Review, *Designs*, **2024**, 8, 3, 49, <https://doi.org/10.3390/designs8030049>.
63. Rivera, M.L., Moukperian, M., Ashbrook, D., Mankoff, J., Hudson, S.E., Stretching the Bounds of 3D Printing with Embedded Textiles, *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, **2017**, <https://doi.org/10.1145/3025453.3025460>.
64. Cui, T.Z., Raji, R.K., Han, J.L., Chen, Y., Avant-Garde Concept in Footwear Research and Design: Review of Application Trends, *Leather and Footwear Journal*, **2024**, 24, 2, 1-10, <https://doi.org/10.24264/lfj.24.2.4>.
65. Waskito, M.A., Mulyana, A., Wahyuning, C.S., Jamaludin, J., Digital Modification Techniques Application on Footwear Upper Decorative Design Process, *Journal of Arts and Humanities*, **2018**, 7, 10, 30-7.
66. Paradiso, J.A., Hsiao, K.-Y., Benbasat, A.Y., Teegarden, Z., Design and Implementation of Expressive Footwear, *IBM Syst J*, **2000**, 39, 3.4, 511-29, <https://doi.org/10.1147/sj.393.0511>.
67. Myers, C.A., Allen, W., Laz, P.J., Lawler-Schwartz, J., Conrad, B.P., The Impact of Self-lacing Technology on Foot Containment during Dynamic Cutting, *Footwear Sci*, **2022**, 14, 2, 94-102, <https://doi.org/10.1080/19424280.2022.2038692>.
68. Pervaia, N., Borshchevska, N., Andreyeva, O., Lypskyi, T., Laser Finishing in the Decoration of Leather Products, *Proceedings of the 9th International Conference on Advanced Materials and Systems - ICAMS 2022*, 26-28 October **2022**, <https://doi.org/10.24264/icams-2022.iii.13>.
69. Borrell, J., González, A., Perez-Vidal, C., Gracia, L., Solanes, J.E., Cooperative Human-Robot Polishing for the Task of Patina Growing on High-quality Leather Shoes, *Int J Adv Manuf Tech*, **2023**, 125, 5, 2467-84, <https://doi.org/10.1007/s00170-022-10620-6>.
70. Cui, T.Z., Raji, R.K., Han, J.L., Chen, Y., Application of 3D Printing Technology in Footwear Design and Manufacture – A Review of Developing Trends, *Text Leather Rev*, **2024**, 7, 1304-21, <https://doi.org/10.31881/TLR.2024.151>.
71. Schmidt, T.W., Scherf, M., Wittwer, D., Schumann, P., Guillén, E., Kastner, J., HAPTIC Digital 3D Printing on Textile Surfaces for High-volume Footwear Manufacturing, *Mater Today: Proc*, **2023**, 93, 31-8, <https://doi.org/10.1016/j.matpr.2023.05.619>.
72. Feuerriegel, S., Hartmann, J., Janiesch, C., Zschech, P., Generative AI, *Bus Inf Syst Eng*, **2024**, 66, 1, 111-26, <https://doi.org/10.1007/s12599-023-00834-7>.
73. Cheng, S.-H., Impact of Generative Artificial Intelligence on Footwear Design Concept and Ideation, *Eng Proc*, **2023**, 55, 1, 32, <https://doi.org/10.3390/engproc2023055032>.
74. Carmigniani, J., Furht, B., Augmented Reality: An Overview, in: Furht, B. (ed.), *Handbook of*

- Augmented Reality*, New York, NY: Springer New York, **2011**, pp. 3-46, [https://doi.org/10.1007/978-1-4614-0064-6\\_1](https://doi.org/10.1007/978-1-4614-0064-6_1).
75. Luh, Y.-P., Wang, J.-B., Chang, J.-W., Chang, S.-Y., Chu, C.-H., Augmented Reality-based Design Customization of Footwear for Children, *J Intell Manuf*, **2013**, 24, 905-17, <https://doi.org/10.1007/s10845-012-0642-9>.
  76. Coetzee, D.R., Albertus, Y., Tam, N., Tucker, R., Conceptualizing Minimalist Footwear: An Objective Definition, *J Sports Sci*, **2018**, 36, 8, 949-54, <https://doi.org/10.1080/02640414.2017.1346816>.
  77. Vibram FiveFingers Men's Bikila [accessed 2025], available from: <https://www.escapesports.ca/vibram-fivefingers-mens-bikila.html>.
  78. Akter, R., Discover the Ugliest Shoes Ever That Will Blow Your Mind, **2024** [accessed 2025], available from: <https://www.cutoutimage.com/blog/ugliest-shoes-ever>.
  79. Sinclair, J., Fau-Goodwin, J., Richards, J., Shore, H., The Influence of Minimalist and Maximalist Footwear on the Kinetics and Kinematics of Running, *Footwear Sci*, **2016**, 8, 1, 33-9, <https://doi.org/10.1080/19424280.2016.1142003>.
  80. Sinclair, J., Richards, J., Shore, H., Effects of Minimalist and Maximalist Footwear on Achilles Tendon Load in Recreational Runners, *Comp Exerc Physiol*, **2015**, 11, 4, 239-44, <https://doi.org/10.3920/CEP150024>.
  81. Marconi, M., Papetti, A., Scafà, M., Rossi, M., Germani, M., An Innovative Framework for Managing the Customization of Tailor-made Shoes, *Proceedings of the Design Society: International Conference on Engineering Design*, **2019**, 1, 1, 3821-30, <https://doi.org/10.1017/dsi.2019.389>.
  82. Adamkiewicz, J., Kochańska, E., Adamkiewicz, I., Łukasik, R.M., Greenwashing and Sustainable Fashion Industry, *Curr Opin Green Sustain Chem*, **2022**, 38, 100710, <https://doi.org/10.1016/j.cogsc.2022.100710>.
  83. de Freitas Netto, S.V., Sobral, M.F.F., Ribeiro, A.R.B., da Luz Soares, G.R., Concepts and Forms of Greenwashing: A Systematic Review, *Environ Sci Eur*, **2020**, 32, 1, 19, <https://doi.org/10.1186/s12302-020-0300-3>.

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# STRUCTURED BIOEMULSIONS BASED ON MIXTURE OF MEMBRANE CONCENTRATED PLANT EXTRACTS WITH APPLICATIONS IN FUNCTIONALIZATION OF TEXTILE MATERIALS

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Received: 14.05.2026

Accepted: 12.06.2026

<https://doi.org/10.24264/lfj.26.2.2>

## STRUCTURED BIOEMULSIONS BASED ON MIXTURE OF MEMBRANE CONCENTRATED PLANT EXTRACTS WITH APPLICATIONS IN FUNCTIONALIZATION OF TEXTILE MATERIALS

**ABSTRACT.** The work refers to the process of obtaining structured bioemulsions based on mixtures of plant extracts (sage, thyme, mint and lemongrass) concentrated by membrane technology, formulated with surfactants (Lauryl glucoside, Tween 20 and Tween 80) and collagen hydrolysate, used for the functionalization of textile materials, giving them antibacterial properties with durability when washed. The bioemulsions are diluted with water in different concentrations and are applied to textile supports made of 100% cotton fibers, by the padding method, in three successive passes, with a take-up degree 85% and pressure of 2.7 bar, followed by a drying step at temperatures of 60°C and 100°C, for approximately 2-5 minutes. A method for validating durability is FTIR-ATR spectroscopy to identify the markers, for calculation of retention rates and analysis of decomposition curves. SEM electron microscopy is used for morphological confirmation of fixation of structured bioemulsions on textile materials even after 5 repeated washing cycles.

**KEYWORDS:** structured bioemulsions, membrane technology, functionalization of textile materials, antibacterial properties and durability when washed

## BIOEMULSII STRUCTURATE PE BAZĂ DE AMESTEC DE EXTRACTE VEGETALE CONCENTRATE PRIN TEHNOLOGIE MEMBRANARĂ, CU APLICAȚII ÎN FUNCȚIONALIZAREA MATERIALELOR TEXTILE

**REZUMAT.** Lucrarea se referă la obținerea de bioemulsii structurate pe bază de amestecuri de extracte din plante (salvie, cimbru, mentă și lemongrass) concentrate prin tehnologie membranară, formulate cu surfactanți (Lauril glucozid, Tween 20 și Tween 80) și hidrolizat de colagen, utilizate pentru funcționalizarea materialelor textile, conferindu-le proprietăți antibacteriene rezistente la spălări repetate. Bioemulsiile sunt diluate cu apă în diferite concentrații și aplicate pe suporturi textile din fibre de bumbac 100%, prin metoda impregnării în trei treceri succesive, cu grad de absorbție de 85% și presiune de 2,7 bari, urmate de o etapă de uscare la temperaturi de 60 °C și 100 °C, timp de aproximativ 2-5 minute. O metodă de validare a durabilității la spălări repetate este spectroscopia FTIR-ATR pentru identificarea markerilor, pentru calcularea ratelor de retenție și analiza curbelor de descompunere. S-a utilizat microscopia electronică SEM pentru confirmarea morfologică a fixării bioemulsiilor structurate pe materialele textile chiar și după 5 cicluri repetate de spălare.

**CUVINTE CHEIE:** bioemulsii structurate, tehnologie membranară, funcționalizarea materialelor textile, proprietăți antibacteriene și durabilitate la spălare

## BIOÉMULSIONS STRUCTURÉES À BASE D'UN MÉLANGE D'EXTRAITS VÉGÉTAUX CONCENTRÉS PAR TECHNOLOGIE MEMBRANAIRE ET LEURS APPLICATIONS DANS LA FONCTIONNALISATION DES MATÉRIAUX TEXTILES

**RÉSUMÉ.** Ce travail porte sur l'obtention de bioémulsions structurées à base de mélanges d'extraits végétaux (sauge, thym, menthe et citronnelle) concentrés par technologie membranaire, formulées avec des tensioactifs (lauryl glucoside, Tween 20 et Tween 80) et de l'hydrolysat de collagène, utilisées pour la fonctionnalisation de matériaux textiles, leur conférant des propriétés antibactériennes qui résistent aux lavages. Les bioémulsions sont diluées dans de l'eau à différentes concentrations et appliquées sur des supports textiles composés de fibres 100 % coton, par la méthode d'encollage, en trois passes successives, avec un taux d'absorption de 85 % et une pression de 2,7 bars, suivies d'une étape de séchage à des températures de 60 °C et 100 °C, pendant environ 2 à 5 minutes. Une méthode de validation de la durabilité consiste à utiliser la spectroscopie FTIR-ATR pour identifier les marqueurs, pour le calcul des taux de rétention et l'analyse des courbes de dégradation. La microscopie électronique à balayage (MEB) est utilisée pour confirmer, d'un point de vue morphologique, la fixation des bioémulsions structurées sur les matériaux textiles, même après cinq cycles de lavage répétés.

**MOTS-CLÉS :** bioémulsions structurées, technologie membranaire, fonctionnalisation des matériaux textiles, propriétés antibactériennes et durabilité au lavage

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## INTRODUCTION

The paper presents the obtaining of structured bioemulsions based on a mixture of surfactants: Lauryl glucoside, Tween 20, Tween 80, with collagen hydrolysate and a mixture of plant extracts, membrane concentrates from: sage, thyme, lemongrass, mint, in equal ratios. The structured bioemulsions created can be used as new additives, auxiliaries in the textile industry, for the functionalization of surfaces. There is an interest in the textile industry to obtain new auxiliaries and replace the classic, toxic and polluting ones [1-10]. The aim is to create auxiliaries that improve the properties of surfaces, be "friendly" with the environment and comply with European pollution standards. The paper also presents a "bio" fixing system on textile surfaces of the obtained bioemulsions, which is innovative, based on biosurfactants and collagen hydrolysate, eliminating the need for synthetic, toxic additives.

The functionalization of textile materials with bioactive compounds of plant origin is a major area of interest, driven by current requirements regarding sustainability, biocompatibility and reducing environmental impact. In this context, numerous technological solutions have been developed aimed at obtaining plant extracts, formulating them in transport systems and applying them to textile supports [1]. Due to the high content of active compounds (polyphenols, flavonoids, volatile oils), plant extracts are used to confer antibacterial, antifungal and antioxidant properties to textile materials [2]. To obtain plant extracts, classical methods of extraction in aqueous or hydroalcoholic medium are known, as well as assisted methods, such as ultrasound or microwave extraction [3]. With the evolution of processing technologies, membrane separation and concentration methods (microfiltration, ultrafiltration, nanofiltration, reverse osmosis) have been developed, which allow the obtaining of concentrated extracts, with a high content of active compounds and improved stability. In this regard, patents RO128610 and RO132969 describe the use of membrane technologies to obtain concentrated plant extracts, rich in

active compounds (polyphenols, flavonoids, saponins, polysaccharides), highlighting the advantages of these methods in terms of purity and separation efficiency [2]. However, these solutions do not address the formulation of extracts in complex dispersed systems nor their use in textile applications.

For the stabilization and application of active compounds on textile supports, the literature documents the use of emulsified systems, microemulsions or bioemulsions, as well as of encapsulation systems, such as microcapsules or coacervates [1-3].

The direct application of plant extracts to textile materials is described in the literature, but, in the absence of appropriate structuring systems, this leads to reduced stability and limited persistence of the functional effect after use and washing cycles. Emulsified systems or bioemulsions are described in which plant extracts are stabilized with ionic or nonionic surfactants and used for the treatment of textile surfaces, these systems being, in some cases, combined with biopolymers or crosslinking agents, in order to increase adhesion to the textile support and resistance to washing [1, 4-6]. However, existing solutions present a series of technological and functional limitations that restrict the effective use of plant extracts in the functionalization of textile materials. Thus, systems based on microcapsules or dispersed particles are generally characterized by relatively large particle sizes and by an uneven distribution on the surface of the textile support, which leads to a reduced treatment efficiency and an uncontrolled release of active compounds [3]. In the case of emulsified systems or classic bioemulsions, their stability is often limited in time, and the internal structure does not always allow for the effective protection of bioactive compounds, especially under conditions of repeated use and washing [2, 3]. In addition, the use of biosurfactants and natural compounds as stabilizing agents for emulsion systems is an emerging direction, highlighting their advantages in terms of biocompatibility and the ecological character of the developed systems [4-6]. Direct application of plant extracts or poorly structured systems leads to

insufficient fixation of the active compounds on the textile support, causing a rapid loss of the functional effect after use and washing cycles [5]. Membrane concentration technologies are mainly used to obtain concentrated plant extracts with a high content of active compounds, but the integration of these extracts into stable and structurally controlled dispersed systems for textile applications is limited or insufficiently developed [7-10]. In most existing solutions, plant extracts are used individually or in simple combinations, without capitalizing on the synergy of complex mixtures and without controlling the architecture of the dispersed systems, which leads to reduced functional efficiency and increased variability of results [10].

Consequently, there is a great need to develop new technological solutions that allow the obtaining of stable, efficient and ecological systems, capable of optimally utilizing bioactive compounds from plant extracts and ensuring improved functional performance of treated textile materials.

## EXPERIMENTAL

### Materials and Methods

The following materials have been used: collagen hydrolysate from Sigma-Aldrich; Lauryl glucoside, Tween 20, Tween 80 from SERVA Feinbiochemica GmbH & Co; sage, thyme, lemongrass, and mint extracts from Hofigal Export Import SA. The structured bioemulsions are characterized by FTIR-ATR spectroscopy, scanning electron microscopy and microbiological tests. The experimental techniques used in this research were performed using:

- a "SEM QUANTA 200" equipment from FEI company, with EDS/EDX coupled. The samples were prepared by slow evaporation in clean atmosphere at room temperature;
- a JASCO FTIR-ATR spectrophotometer.

The plant extract concentration experiments were performed on a KMS Laboratory Cell CF-1 module, equipped with prefiltration, microfiltration and ultrafiltration membranes from Sigma-Aldrich (Figure 1).



Figure 1. Image of a KMS Laboratory Cell CF-1 module

## RESULTS AND DISCUSSIONS

### Obtaining Membrane-Concentrated Plant Extracts

In the first stage, the vegetable extracts of sage, thyme, lemongrass and mint are obtained, used in the mixture, in equal proportions. The extraction is carried out in an aqueous or hydroalcoholic medium (water: ethanol ratio 1:1), at temperatures of 20-60°C, for 30-120 minutes, using a solid:liquid ratio of 1:10-1:20. The extracts obtained are

subsequently subjected to a concentration process by coupled membrane technology, using microfiltration, ultrafiltration and/or nanofiltration modules. The process is carried out at working pressures between 2 and 8 bar, temperatures of 23-30°C and durations of approximately 30-60 minutes. Under these conditions, a concentrated retentate is obtained, with a content of bioactive compounds approximately 1.5-2 times higher than the initial extract, characterized by an increased content of bioactive compounds compared to the initial extract (Figure 2).

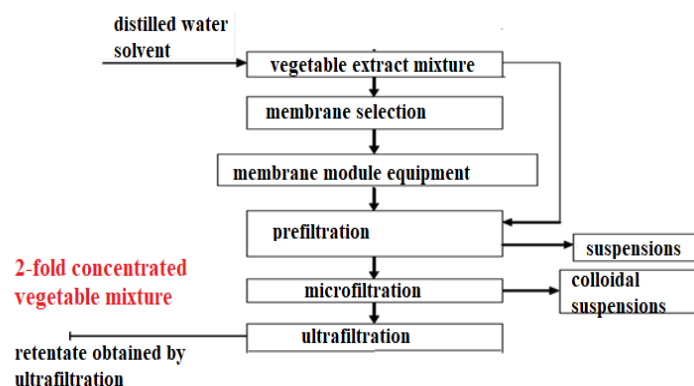


Figure 2. Technological flow for obtaining the mixture of vegetable extract from: sage, thyme, lemongrass, mint, concentrated through membranes

### Obtaining Structured Bioemulsions Based on a Mixture of Membrane-Concentrated Plant Extracts

In the next stage, the concentrated extracts are integrated into a dispersed system by formulating bioemulsions. For this purpose, a system of surfactants is used, consisting of Lauryl glucoside, Tween 20 and Tween 80, in concentrations of 3% each, together with collagen hydrolysate in a concentration of 1%. The dispersion medium is represented by a water:ethanol mixture in a 1:1 ratio. The emulsification process is carried out under controlled temperature and stirring conditions, in two successive stages: i) in the first stage,

the surfactants are dissolved and homogenized by stirring at room temperature (20-25°C), for 30-60 minutes, at speeds of 800-1200 rpm; ii) in the second stage, the collagen hydrolysate and the mixture of membrane-concentrated plant extracts are added, with subsequent adjustment of the pH to values close to neutral (5.5-7). Subsequently, the system is homogenized at temperatures up to 50°C, for 30-60 minutes. Under these conditions, multiple structured bioemulsions are formed, of the “emulsion in emulsion” type, with particle sizes in the nano- and micrometric range, of approximately 50-200 nm (Figure 3).

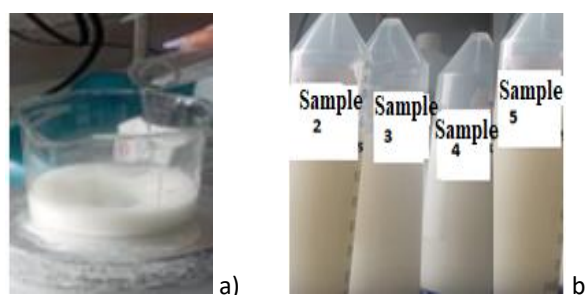


Figure 3. Photographic images of: **sample 1** – multiple emulsion based on Tween 20/Tween 80/Lauryl Glucoside and collagen hydrolysate mixture and membrane-concentrated vegetable extract mixture of: sage, thyme, lemongrass, mint; **sample 2** – multiple emulsion based on Tween 20/Tween 80/Lauryl Glucoside and collagen hydrolysate mixture and membrane-concentrated lemongrass extract; **sample 3** – multiple emulsion based on Tween 20/Tween 80/Lauryl Glucoside and collagen hydrolysate mixture and membrane-concentrated thyme extract; **sample 4** – multiple emulsion based on Tween 20/Tween 80/Lauryl Glucoside and collagen hydrolysate mixture and membrane-concentrated sage extract; **sample 5** – multiple emulsion based on Tween 20/Tween 80/Lauryl Glucoside and mixture of collagen hydrolysate and membrane-concentrated mint extract

These are stabilized by the interaction between surfactants and collagen hydrolysate, forming a “bio” type fixation system, which

facilitates the anchoring of active compounds on the surface of textile fibers.

### Functionalization of Textile Materials Using the Structured Bioemulsions Created

Sample 1 from Figure 3 was selected, dilutions of 2%, 10%, 20%, 50% and 100% were prepared and applied, by the pad method, on 100% cotton textile material. The treatment is followed by drying at temperatures of 60°C and 100°C, for 2-5 minutes. The 100% cotton textile material was tested for antibacterial activity, according to the standardized method SR EN ISO 20645:2004, using reference bacterial strains (*Escherichia coli* ATCC 11229 and *Staphylococcus aureus* ATCC 6538). To evaluate the durability of the applied treatments, the textile materials that showed the best results in terms of antibacterial effect were selected and subjected to 1, 2 and 5 washing cycles, these being represented by textile materials made of 100% cotton fibers, cotton fibers treated with 50% and 100% bioemulsion dilutions, dried at 60°C and

100°C. Microbiological tests carried out according to EN ISO 20645/2004 confirm good antibacterial, antifungal effects (with inhibition zones of 1-18.5 mm) before washing. They were carried out on selected textiles, 1, 2 and 5 washing cycles. After 5 washing cycles, the effects are maintained satisfactorily (lack of bacterial or fungal growth under the sample), demonstrating the efficiency of fixing bioemulsions on textiles, impregnated (Table 1).

The following notation was made for the sectioned samples, initially with the applied emulsion dilution of 50% and 100%, on 100% cotton (code A) by drying at 60°C and 100°C: Ai-A50/100, Ai-A100/100, Ai-A50/60, Ai-A100/60 and after one wash cycle with: Ai-A50/100S1, Ai-A100/100S1, Ai-A50/60S1, Ai-A100/60S1, after two wash cycles: Ai-A50/100S2, Ai-A100/100S2, Ai-A50/60S2, Ai-A100/60S2 and after 5 wash cycles with: Ai-A50/100S5, Ai-A100/100S5, Ai-A50/60S5, Ai-A100/60S5.

Table 1: Experimental results for determining the antibacterial effect of samples immobilized on 100% cotton textile material (code A) before washing and after 1, 2, 5 washing cycles

| Sample                     | <i>Escherichia coli</i> |                           | <i>Staphylococcus aureus</i> |                           |
|----------------------------|-------------------------|---------------------------|------------------------------|---------------------------|
|                            | Inhibition zone (mm)    | Effect evaluation         | Inhibition zone (mm)         | Effect evaluation         |
| Control sample             | 0                       | Insufficient              | 0                            | Insufficient              |
| Ai-A50/100                 | 11                      | Good antibacterial effect | 14                           | Good antibacterial effect |
| Ai-A100/100                | 18                      | Good antibacterial effect | 16                           | Good antibacterial effect |
| Ai-A50/60                  | 12                      | Good antibacterial effect | 10                           | Good antibacterial effect |
| Ai-A100/60                 | 18.5                    | Good antibacterial effect | 17                           | Good antibacterial effect |
| <i>After 1 wash cycle</i>  |                         |                           |                              |                           |
| Ai-A50/100                 | 4                       | Satisfactory              | 2.5                          | Satisfactory              |
| Ai-A100/100                | 15                      | Satisfactory              | 15.5                         | Satisfactory              |
| Ai-A50/60                  | 4                       | Satisfactory              | 5                            | Satisfactory              |
| Ai-A100/60                 | 6                       | Satisfactory              | 10                           | Satisfactory              |
| <i>After 2 wash cycles</i> |                         |                           |                              |                           |
| Ai-A50/100                 | 3                       | Satisfactory              | 3                            | Satisfactory              |
| Ai-A100/100                | 5                       | Satisfactory              | 3.5                          | Satisfactory              |
| Ai-A50/60                  | 2                       | Satisfactory              | 1                            | Satisfactory              |
| Ai-A100/60                 | 1                       | Satisfactory              | 2.5                          | Satisfactory              |
| <i>After 5 wash cycles</i> |                         |                           |                              |                           |
| Ai-A50/100                 |                         | Satisfactory              |                              | Satisfactory              |
| Ai-A100/100                |                         | Satisfactory              |                              | Satisfactory              |
| Ai-A50/60                  |                         | Satisfactory              |                              | Satisfactory              |
| Ai-A100/60                 |                         | Satisfactory              |                              | Satisfactory              |



### Characterization of Functionalized Textile Materials with the Structured Bioemulsions Created

The characterization of the treated textile materials was carried out by specific methods, such as microbiological tests, FTIR-ATR spectroscopy and scanning electron microscopy (SEM) coupled with EDS/EDX analysis (Table 2). A method for validation of durability (persistence) was presented,

characterized by the use of FTIR-ATR spectroscopy for the identification of markers: thymol from thyme extract at  $\nu = 1580 \text{ cm}^{-1}$  (aromatic ring); aldehydes from lemongrass extract at  $\nu = 1672 \text{ cm}^{-1}$ ; menthol from mint extract at  $\nu = 1710 \text{ cm}^{-1}$  (Ketone); 1,8-Cineole from sage extract at  $\nu = 1080 \text{ cm}^{-1}$  (ether) and for the calculation of retention rates and the analysis of the decomposition curves, respectively (Figures 4-7).

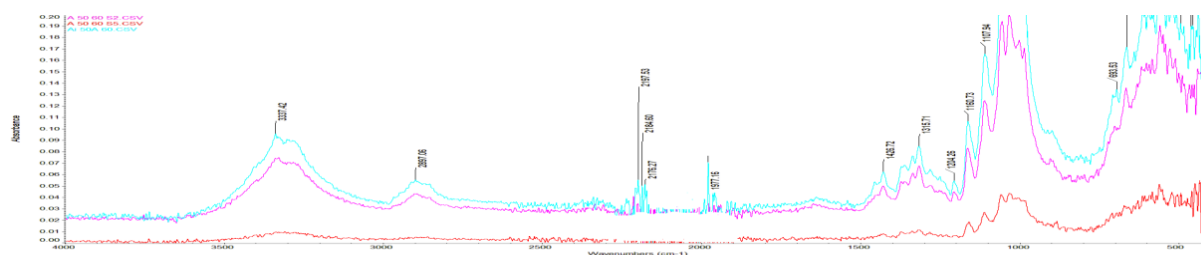


Figure 4. Detail of the FTIR-ATR spectra overlay for samples: Ai-50A/60, A-50/60S2, A-50A/60S5

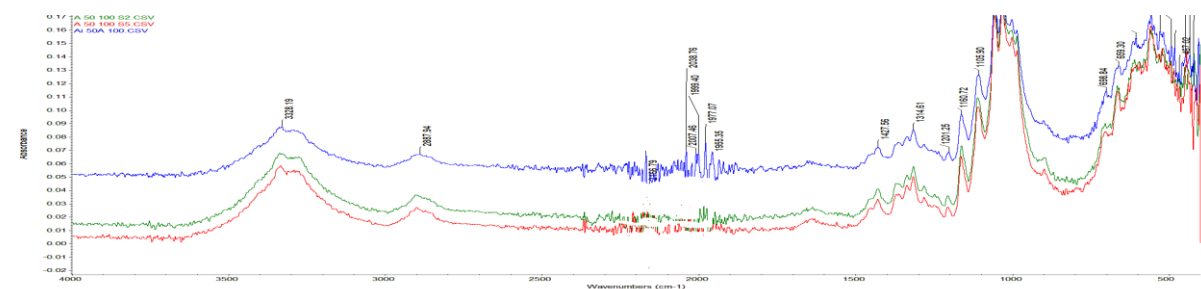


Figure 5. Detail of the FTIR-ATR spectra overlay for samples: Ai-50A/100, A-50A/100S2, A-50A/100S5

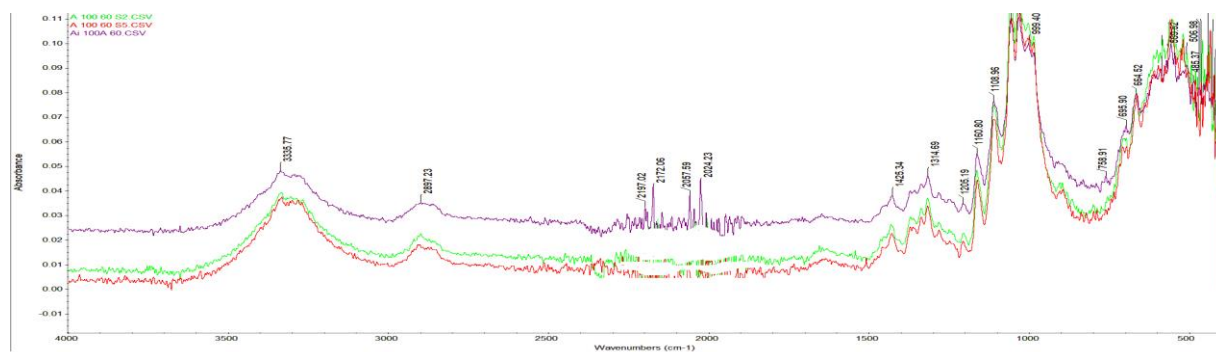


Figure 6. Detail of the FTIR-ATR spectra overlay for samples: Ai-100A/60, A-100A/60S2, A-100A/60S5

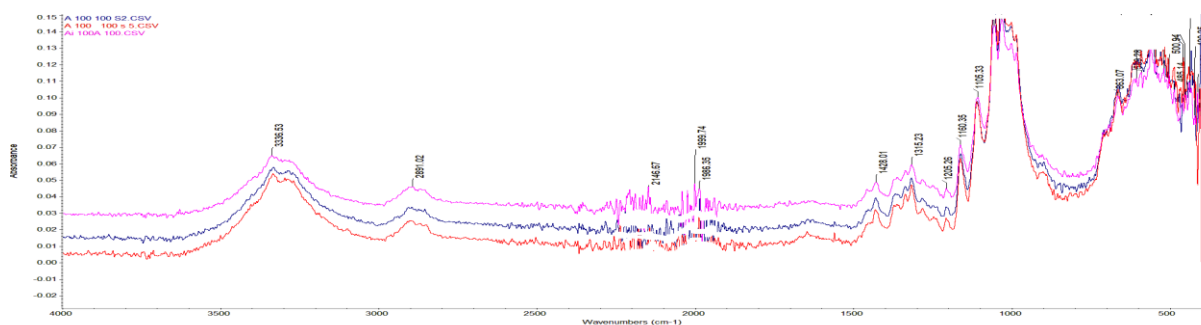


Figure 7. Detail of the FTIR-ATR spectra overlay for samples: Ai-100A100, A-100A/100S2, A-100A/100S5

The calculation of retention rates shows that a significant percentage of vegetable mixture remains on cotton treated at 100°C (for sample A-50A/100S5 – 32.95%) after 5

washing cycles, compared to impregnation at 60°C (for sample A-50A/60S5 – 4%), for the same initial mixture concentration but different drying temperatures (Table 2).

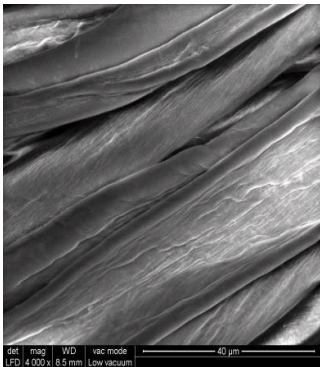
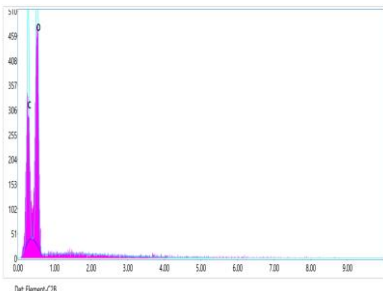
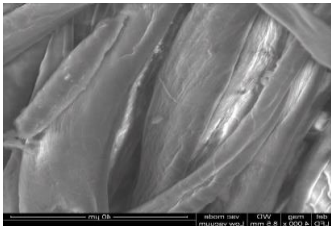
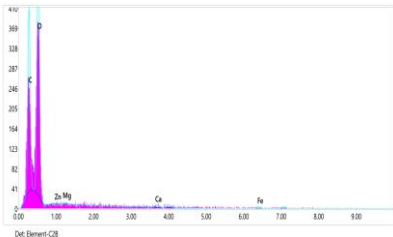
Table 2: Calculation of retention rates for samples selected

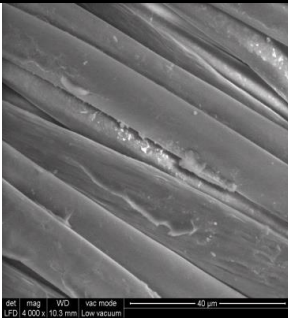
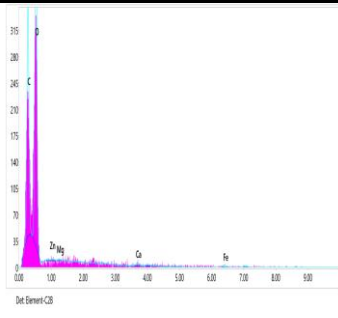
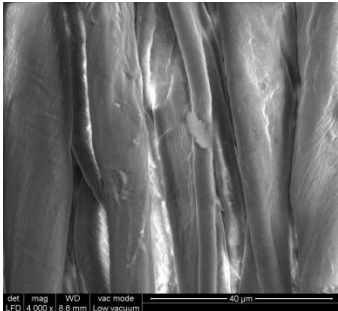
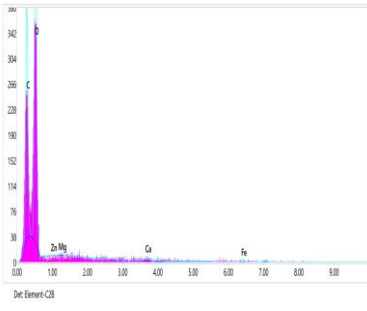
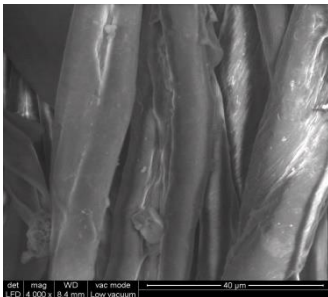
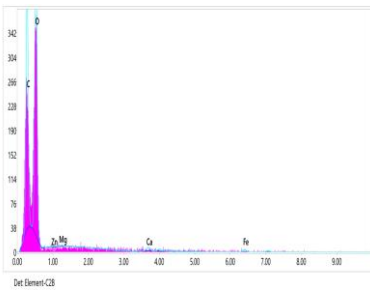
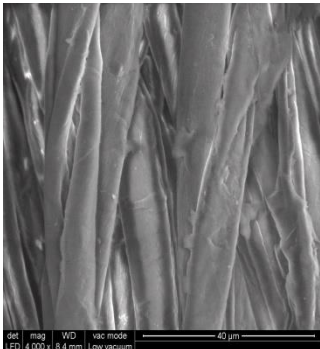
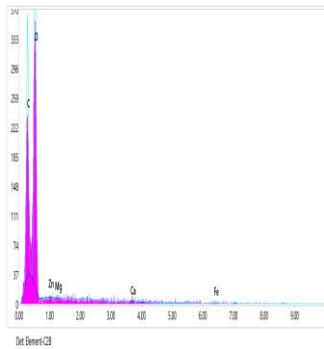
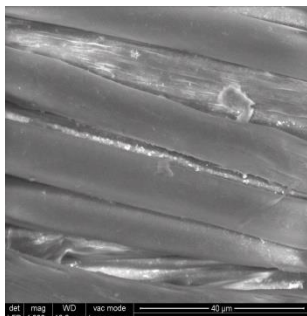
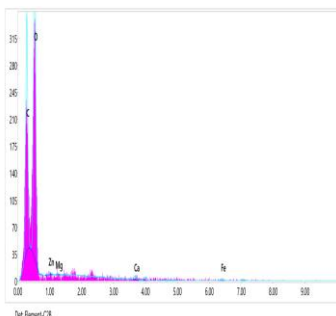
| Sample        | Absorbance at 2897 cm <sup>-1</sup> | Retention rates (%) |
|---------------|-------------------------------------|---------------------|
| Ai-A50A/60    | 0.082                               | 50                  |
| A-A50/60S2    | 0.038                               | 46                  |
| A-A50/60S5    | 0.003                               | 4                   |
| Ai-A50A/100   | 0.088                               | 50                  |
| A-50/100S2    | 0.068                               | 38.64               |
| A-50/100S5    | 0.058                               | 32.95               |
| Ai-A100A/60   | 0.035                               | 100                 |
| A-A100A/60S2  | 0.018                               | 51.4                |
| A-A100A/60S5  | 0.014                               | 40                  |
| Ai-A100A/100  | 0.046                               | 100                 |
| Ai-100A/100S2 | 0.033                               | 71.7                |
| Ai-100A/100S5 | 0.025                               | 54.3                |

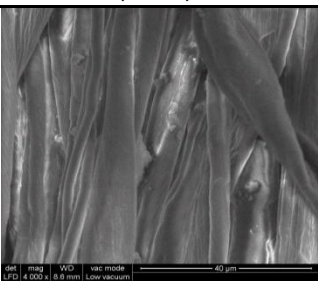
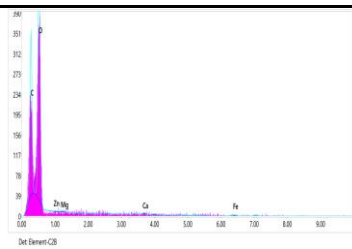
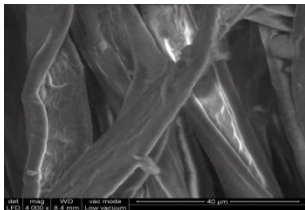
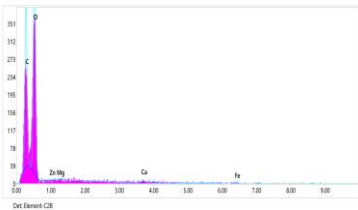
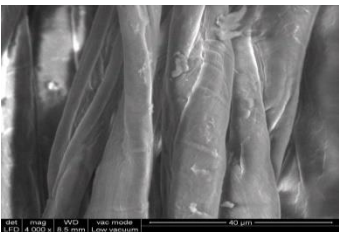
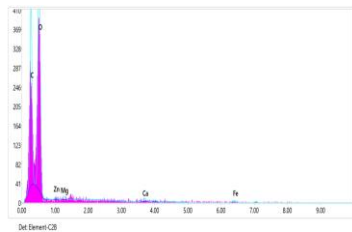
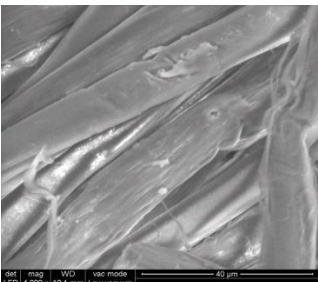
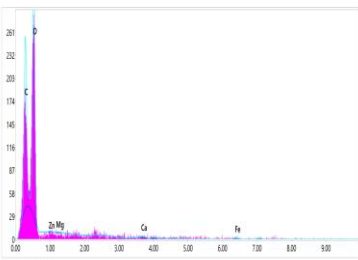
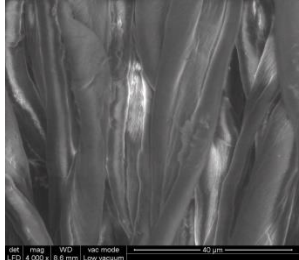
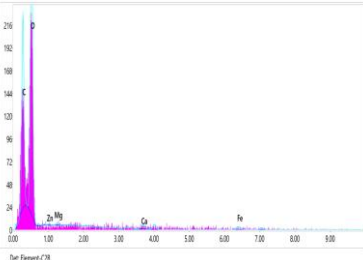
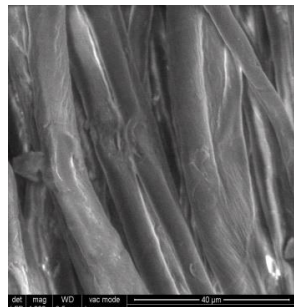
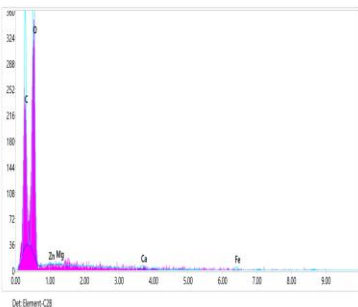
Morphological analysis performed by scanning electron microscopy (SEM) highlights the uniform distribution of the bioemulsified system on the surface of textile fibers. EDS/EDX analysis of selected samples highlights the presence of the majority of mineral elements, specific to each extract (sage, mint, lemongrass, thyme) even after 5 washing cycles, which demonstrates good

resistance to washing of the treatments performed, even in the absence of commonly used fixing agents (Table 3). Influence of technological parameters – increasing the drying temperature to 100°C – leads to more efficient fixing and increased stability to washing, with possible variations in the intensity of the antibacterial effect.

Table 3: SEM and EDS/EDX images for all samples analyzed before and after 2 and 5 washing cycles, respectively

| Sample                  | SEM image (x4000)                                                                   | EDS/EDX image                                                                        | eZAF Quant Result - Analysis<br>Uncertainty: 9.40 %                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|-------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|----------|----------|---------|-----|------|------|------|-----|------|------|-----|------|-----|-----|------|------|-----|-----|------|------|-----|-----|------|------|-----|-----|------|
| Control sample (code A) |  |  | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>40.9</td><td>48.0</td><td>9.7</td></tr><tr><td>O K</td><td>59.1</td><td>52.0</td><td>9.7</td></tr></table>                                                                                                                                                                                                                                              | Element  | Weight % | Atomic % | Error % | C K | 40.9 | 48.0 | 9.7  | O K | 59.1 | 52.0 | 9.7 |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| C K                     | 40.9                                                                                | 48.0                                                                                 | 9.7                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| O K                     | 59.1                                                                                | 52.0                                                                                 | 9.7                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Ai-A50/100 (100°C)      |  |  | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.9</td><td>47.5</td><td>10.3</td></tr><tr><td>O K</td><td>53.1</td><td>49.9</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.2</td><td>0.2</td><td>73.5</td></tr><tr><td>Ca K</td><td>1.4</td><td>0.5</td><td>58.7</td></tr><tr><td>Fe K</td><td>7.1</td><td>1.9</td><td>24.3</td></tr><tr><td>Zn L</td><td>0.2</td><td>0.0</td><td>74.8</td></tr></table> | Element  | Weight % | Atomic % | Error % | C K | 37.9 | 47.5 | 10.3 | O K | 53.1 | 49.9 | 9.8 | Mg K | 0.2 | 0.2 | 73.5 | Ca K | 1.4 | 0.5 | 58.7 | Fe K | 7.1 | 1.9 | 24.3 | Zn L | 0.2 | 0.0 | 74.8 |
| Element                 | Weight %                                                                            | Atomic %                                                                             | Error %                                                                                                                                                                                                                                                                                                                                                                                                                                                       |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| C K                     | 37.9                                                                                | 47.5                                                                                 | 10.3                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| O K                     | 53.1                                                                                | 49.9                                                                                 | 9.8                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Mg K                    | 0.2                                                                                 | 0.2                                                                                  | 73.5                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Ca K                    | 1.4                                                                                 | 0.5                                                                                  | 58.7                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Fe K                    | 7.1                                                                                 | 1.9                                                                                  | 24.3                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Zn L                    | 0.2                                                                                 | 0.0                                                                                  | 74.8                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |

| Sample                  | SEM image<br>(x4000)                                                                | EDS/EDX image                                                                        | eZAF Quant Result - Analysis<br>Uncertainty: 9.40 %                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|-------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|----------|----------|---------|-----|------|------|------|-----|------|------|-----|------|-----|-----|------|------|-----|-----|------|------|-----|-----|------|------|-----|-----|------|
| Ai-A100/100<br>(100°C)  |    |    | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.2</td><td>46.8</td><td>10.5</td></tr><tr><td>O K</td><td>53.4</td><td>50.5</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.2</td><td>0.1</td><td>77.4</td></tr><tr><td>Ca K</td><td>1.5</td><td>0.5</td><td>65.0</td></tr><tr><td>Fe K</td><td>7.4</td><td>2.0</td><td>17.4</td></tr><tr><td>Zn L</td><td>0.3</td><td>0.1</td><td>74.8</td></tr></table> | Element  | Weight % | Atomic % | Error % | C K | 37.2 | 46.8 | 10.5 | O K | 53.4 | 50.5 | 9.8 | Mg K | 0.2 | 0.1 | 77.4 | Ca K | 1.5 | 0.5 | 65.0 | Fe K | 7.4 | 2.0 | 17.4 | Zn L | 0.3 | 0.1 | 74.8 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 37.2     | 46.8     | 10.5     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 53.4     | 50.5     | 9.8      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 0.2      | 0.1      | 77.4     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 1.5      | 0.5      | 65.0     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Fe K                    | 7.4                                                                                 | 2.0                                                                                  | 17.4                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Zn L                    | 0.3                                                                                 | 0.1                                                                                  | 74.8                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Ai-A50/60<br>(60°C)     |    |    | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.6</td><td>47.4</td><td>10.4</td></tr><tr><td>O K</td><td>52.3</td><td>49.6</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.2</td><td>0.1</td><td>74.1</td></tr><tr><td>Ca K</td><td>1.8</td><td>0.7</td><td>46.1</td></tr><tr><td>Fe K</td><td>8.0</td><td>2.2</td><td>21.2</td></tr><tr><td>Zn L</td><td>0.1</td><td>0.0</td><td>99.0</td></tr></table> | Element  | Weight % | Atomic % | Error % | C K | 37.6 | 47.4 | 10.4 | O K | 52.3 | 49.6 | 9.8 | Mg K | 0.2 | 0.1 | 74.1 | Ca K | 1.8 | 0.7 | 46.1 | Fe K | 8.0 | 2.2 | 21.2 | Zn L | 0.1 | 0.0 | 99.0 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 37.6     | 47.4     | 10.4     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 52.3     | 49.6     | 9.8      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 0.2      | 0.1      | 74.1     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 1.8      | 0.7      | 46.1     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Fe K                    | 8.0                                                                                 | 2.2                                                                                  | 21.2                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Zn L                    | 0.1                                                                                 | 0.0                                                                                  | 99.0                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Ai-A100/60<br>(60°C)    |   |   | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>39.0</td><td>48.9</td><td>10.3</td></tr><tr><td>O K</td><td>51.3</td><td>48.2</td><td>9.9</td></tr><tr><td>Mg K</td><td>0.2</td><td>0.1</td><td>77.8</td></tr><tr><td>Ca K</td><td>1.6</td><td>0.6</td><td>46.5</td></tr><tr><td>Fe K</td><td>7.9</td><td>2.1</td><td>20.3</td></tr><tr><td>Zn L</td><td>0.1</td><td>0.0</td><td>86.7</td></tr></table> | Element  | Weight % | Atomic % | Error % | C K | 39.0 | 48.9 | 10.3 | O K | 51.3 | 48.2 | 9.9 | Mg K | 0.2 | 0.1 | 77.8 | Ca K | 1.6 | 0.6 | 46.5 | Fe K | 7.9 | 2.1 | 20.3 | Zn L | 0.1 | 0.0 | 86.7 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 39.0     | 48.9     | 10.3     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 51.3     | 48.2     | 9.9      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 0.2      | 0.1      | 77.8     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 1.6      | 0.6      | 46.5     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Fe K                    | 7.9                                                                                 | 2.1                                                                                  | 20.3                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Zn L                    | 0.1                                                                                 | 0.0                                                                                  | 86.7                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| After 2 wash cycles     |                                                                                     |                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                               |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| A-A50/100S2<br>(100°C)  |  |  | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.4</td><td>47.0</td><td>10.5</td></tr><tr><td>O K</td><td>53.3</td><td>50.3</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.3</td><td>0.2</td><td>73.9</td></tr><tr><td>Ca K</td><td>1.2</td><td>0.4</td><td>65.4</td></tr><tr><td>Fe K</td><td>7.6</td><td>2.1</td><td>33.9</td></tr><tr><td>Zn L</td><td>0.3</td><td>0.1</td><td>75.5</td></tr></table> | Element  | Weight % | Atomic % | Error % | C K | 37.4 | 47.0 | 10.5 | O K | 53.3 | 50.3 | 9.8 | Mg K | 0.3 | 0.2 | 73.9 | Ca K | 1.2 | 0.4 | 65.4 | Fe K | 7.6 | 2.1 | 33.9 | Zn L | 0.3 | 0.1 | 75.5 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 37.4     | 47.0     | 10.5     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 53.3     | 50.3     | 9.8      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 0.3      | 0.2      | 73.9     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 1.2      | 0.4      | 65.4     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Fe K                    | 7.6                                                                                 | 2.1                                                                                  | 33.9                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Zn L                    | 0.3                                                                                 | 0.1                                                                                  | 75.5                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| A-A100/100S2<br>(100°C) |  |  | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.3</td><td>47.0</td><td>10.5</td></tr><tr><td>O K</td><td>53.0</td><td>50.2</td><td>9.9</td></tr><tr><td>Mg K</td><td>0.1</td><td>0.1</td><td>80.8</td></tr><tr><td>Ca K</td><td>1.7</td><td>0.7</td><td>49.0</td></tr><tr><td>Fe K</td><td>7.3</td><td>2.0</td><td>20.7</td></tr><tr><td>Zn L</td><td>0.5</td><td>0.1</td><td>73.9</td></tr></table> | Element  | Weight % | Atomic % | Error % | C K | 37.3 | 47.0 | 10.5 | O K | 53.0 | 50.2 | 9.9 | Mg K | 0.1 | 0.1 | 80.8 | Ca K | 1.7 | 0.7 | 49.0 | Fe K | 7.3 | 2.0 | 20.7 | Zn L | 0.5 | 0.1 | 73.9 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 37.3     | 47.0     | 10.5     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 53.0     | 50.2     | 9.9      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 0.1      | 0.1      | 80.8     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 1.7      | 0.7      | 49.0     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Fe K                    | 7.3                                                                                 | 2.0                                                                                  | 20.7                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |
| Zn L                    | 0.5                                                                                 | 0.1                                                                                  | 73.9                                                                                                                                                                                                                                                                                                                                                                                                                                                          |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |     |     |      |      |     |     |      |

| Sample                  | SEM image<br>(x4000)                                                                | EDS/EDX image                                                                        | eZAF Quant Result - Analysis<br>Uncertainty: 9.40 %                                                                                                                                                                                                                                                                                                                                                                                                            |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|-------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|----------|----------|---------|-----|------|------|------|-----|------|------|-----|------|-----|-----|------|------|-----|-----|------|------|------|-----|------|------|-----|-----|------|
| A-A50/60S2<br>(60°C)    |    |    | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.4</td><td>46.0</td><td>10.4</td></tr><tr><td>O K</td><td>56.5</td><td>52.2</td><td>9.7</td></tr><tr><td>Mg K</td><td>0.2</td><td>0.1</td><td>74.7</td></tr><tr><td>Ca K</td><td>0.9</td><td>0.3</td><td>69.5</td></tr><tr><td>Fe K</td><td>4.9</td><td>1.3</td><td>68.6</td></tr><tr><td>Zn L</td><td>0.1</td><td>0.0</td><td>84.9</td></tr></table>  | Element  | Weight % | Atomic % | Error % | C K | 37.4 | 46.0 | 10.4 | O K | 56.5 | 52.2 | 9.7 | Mg K | 0.2 | 0.1 | 74.7 | Ca K | 0.9 | 0.3 | 69.5 | Fe K | 4.9  | 1.3 | 68.6 | Zn L | 0.1 | 0.0 | 84.9 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 37.4     | 46.0     | 10.4     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 56.5     | 52.2     | 9.7      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0.2      | 0.1      | 74.7     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0.9      | 0.3      | 69.5     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Fe K                    | 4.9                                                                                 | 1.3                                                                                  | 68.6                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Zn L                    | 0.1                                                                                 | 0.0                                                                                  | 84.9                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| A-A100/60S2<br>(60°C)   |    |    | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>38.0</td><td>47.8</td><td>10.4</td></tr><tr><td>O K</td><td>52.4</td><td>49.4</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.2</td><td>0.1</td><td>72.2</td></tr><tr><td>Ca K</td><td>1.4</td><td>0.5</td><td>63.9</td></tr><tr><td>Fe K</td><td>7.8</td><td>2.1</td><td>32.2</td></tr><tr><td>Zn L</td><td>0.2</td><td>0.0</td><td>75.3</td></tr></table>  | Element  | Weight % | Atomic % | Error % | C K | 38.0 | 47.8 | 10.4 | O K | 52.4 | 49.4 | 9.8 | Mg K | 0.2 | 0.1 | 72.2 | Ca K | 1.4 | 0.5 | 63.9 | Fe K | 7.8  | 2.1 | 32.2 | Zn L | 0.2 | 0.0 | 75.3 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 38.0     | 47.8     | 10.4     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 52.4     | 49.4     | 9.8      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0.2      | 0.1      | 72.2     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1.4      | 0.5      | 63.9     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Fe K                    | 7.8                                                                                 | 2.1                                                                                  | 32.2                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Zn L                    | 0.2                                                                                 | 0.0                                                                                  | 75.3                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| After 5 wash cycles     |                                                                                     |                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| A-A50/100S5<br>(100°C)  |   |   | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.7</td><td>47.8</td><td>10.4</td></tr><tr><td>O K</td><td>51.4</td><td>48.9</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.4</td><td>0.3</td><td>67.5</td></tr><tr><td>Ca K</td><td>2.0</td><td>0.8</td><td>40.8</td></tr><tr><td>Fe K</td><td>8.0</td><td>2.2</td><td>28.8</td></tr><tr><td>Zn L</td><td>0.4</td><td>0.1</td><td>72.7</td></tr></table>  | Element  | Weight % | Atomic % | Error % | C K | 37.7 | 47.8 | 10.4 | O K | 51.4 | 48.9 | 9.8 | Mg K | 0.4 | 0.3 | 67.5 | Ca K | 2.0 | 0.8 | 40.8 | Fe K | 8.0  | 2.2 | 28.8 | Zn L | 0.4 | 0.1 | 72.7 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 37.7     | 47.8     | 10.4     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 51.4     | 48.9     | 9.8      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0.4      | 0.3      | 67.5     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 2.0      | 0.8      | 40.8     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Fe K                    | 8.0                                                                                 | 2.2                                                                                  | 28.8                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Zn L                    | 0.4                                                                                 | 0.1                                                                                  | 72.7                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| A-A100/100S5<br>(100°C) |  |  | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>32.1</td><td>41.8</td><td>12.7</td></tr><tr><td>O K</td><td>55.7</td><td>54.6</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.1</td><td>0.1</td><td>92.6</td></tr><tr><td>Ca K</td><td>1.4</td><td>0.6</td><td>66.8</td></tr><tr><td>Fe K</td><td>10.4</td><td>2.9</td><td>22.8</td></tr><tr><td>Zn L</td><td>0.3</td><td>0.1</td><td>87.4</td></tr></table> | Element  | Weight % | Atomic % | Error % | C K | 32.1 | 41.8 | 12.7 | O K | 55.7 | 54.6 | 9.8 | Mg K | 0.1 | 0.1 | 92.6 | Ca K | 1.4 | 0.6 | 66.8 | Fe K | 10.4 | 2.9 | 22.8 | Zn L | 0.3 | 0.1 | 87.4 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 32.1     | 41.8     | 12.7     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 55.7     | 54.6     | 9.8      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0.1      | 0.1      | 92.6     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1.4      | 0.6      | 66.8     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Fe K                    | 10.4                                                                                | 2.9                                                                                  | 22.8                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Zn L                    | 0.3                                                                                 | 0.1                                                                                  | 87.4                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| A-A50/60S5<br>(60°C)    |  |  | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>38.1</td><td>47.2</td><td>10.3</td></tr><tr><td>O K</td><td>54.7</td><td>50.8</td><td>9.8</td></tr><tr><td>Mg K</td><td>0.1</td><td>0.0</td><td>89.7</td></tr><tr><td>Ca K</td><td>1.3</td><td>0.5</td><td>63.8</td></tr><tr><td>Fe K</td><td>5.7</td><td>1.5</td><td>41.5</td></tr><tr><td>Zn L</td><td>0.1</td><td>0.0</td><td>76.0</td></tr></table>  | Element  | Weight % | Atomic % | Error % | C K | 38.1 | 47.2 | 10.3 | O K | 54.7 | 50.8 | 9.8 | Mg K | 0.1 | 0.0 | 89.7 | Ca K | 1.3 | 0.5 | 63.8 | Fe K | 5.7  | 1.5 | 41.5 | Zn L | 0.1 | 0.0 | 76.0 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 38.1     | 47.2     | 10.3     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 54.7     | 50.8     | 9.8      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0.1      | 0.0      | 89.7     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1.3      | 0.5      | 63.8     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Fe K                    | 5.7                                                                                 | 1.5                                                                                  | 41.5                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Zn L                    | 0.1                                                                                 | 0.0                                                                                  | 76.0                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| A-A100/60S5<br>(60°C)   |  |  | <table><tr><th>Element</th><th>Weight %</th><th>Atomic %</th><th>Error %</th></tr><tr><td>C K</td><td>37.8</td><td>48.0</td><td>10.5</td></tr><tr><td>O K</td><td>51.2</td><td>48.8</td><td>9.9</td></tr><tr><td>Mg K</td><td>0.1</td><td>0.1</td><td>74.8</td></tr><tr><td>Ca K</td><td>1.5</td><td>0.6</td><td>62.1</td></tr><tr><td>Fe K</td><td>9.2</td><td>2.5</td><td>20.3</td></tr><tr><td>Zn L</td><td>0.2</td><td>0.0</td><td>82.9</td></tr></table>  | Element  | Weight % | Atomic % | Error % | C K | 37.8 | 48.0 | 10.5 | O K | 51.2 | 48.8 | 9.9 | Mg K | 0.1 | 0.1 | 74.8 | Ca K | 1.5 | 0.6 | 62.1 | Fe K | 9.2  | 2.5 | 20.3 | Zn L | 0.2 | 0.0 | 82.9 |
|                         |                                                                                     |                                                                                      | Element                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Weight % | Atomic % | Error %  |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | C K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 37.8     | 48.0     | 10.5     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | O K                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 51.2     | 48.8     | 9.9      |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Mg K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0.1      | 0.1      | 74.8     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
|                         |                                                                                     |                                                                                      | Ca K                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 1.5      | 0.6      | 62.1     |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Fe K                    | 9.2                                                                                 | 2.5                                                                                  | 20.3                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |
| Zn L                    | 0.2                                                                                 | 0.0                                                                                  | 82.9                                                                                                                                                                                                                                                                                                                                                                                                                                                           |          |          |          |         |     |      |      |      |     |      |      |     |      |     |     |      |      |     |     |      |      |      |     |      |      |     |     |      |



## CONCLUSIONS

After 1, 2 and 5 washing cycles, textile samples treated with bioemulsions based on plant extract mixtures continue to exhibit antibacterial effect, which indicates good fixation of the bioactive compounds on the support. The intensity of this effect is maintained for all the analyzed variants, but is mainly influenced by the concentration of the bioemulsion, the samples treated at higher concentrations showing both a more pronounced antibacterial activity and a superior durability to washing.

Technological parameters play an essential role in determining the efficiency of the treatment and its durability, influencing both the degree of immobilization of the active compounds on the textile support and their stability to washing, aspects highlighted by correlating the results obtained by FTIR-ATR and SEM coupled with EDS/EDX, as follows:

- the amount of immobilized bioactive compounds, highlighted by FTIR-ATR spectroscopy, increases with the concentration of the bioemulsion;
- the drying operation performed after padding, at 100°C, leads to more efficient fixation and increased washing stability, through improved anchoring of the compounds on the surface of the textile support;
- high temperatures may cause a partial decrease in antibacterial activity, associated with the volatilization or degradation of some bioactive compounds from the composition of the plant extracts constituting the bioemulsion.

## Acknowledgments

The works were supported by Romanian Ministry of Research and Innovation and CCCDI–UEFISCDI, Nucleu Program, PN 23 26 01 04 (Tex4Age).

## REFERENCES

1. Rahaman, S.M., Bhattarai, A., Kumar, D., Singh, B., Saha, B., Application of Biosurfactants as Emulsifiers in the Processing of Food Products with Diverse Utilization in the Baked Goods, in Inamuddin and C.O. Adetunji (eds.), *Applications of Next Generation Biosurfactants in the Food Sector*, **2022**, 203-237, <https://doi.org/10.1016/B978-0-12-824283-4.00021-6>.
2. Yorgancioglu, A., Emulsification and Application of a Thymol Loaded Antibacterial Fatliquor for Leather Industry, *J Ind Text*, **2020**, 51, 3, 470-485, <https://doi.org/10.1177/1528083720941117>.
3. Hu, Y.T., Ting, Y., Hu, J.-Y., Hsieh, S.C., Techniques and Methods to Study Functional Characteristics of Emulsion Systems, *J Food Drug Anal*, **2017**, 25, 1, 16-26, <https://doi.org/10.1016/j.jfda.2016.10.021>.
4. Guo, R., Li, Y., Dong, A., Yang, X., Protein-Based Emulsion Gels as Materials for Delivery of Bioactive Substances: Formation, Structures, Applications and Challenges, *Food Hydrocolloids*, **2023**, 144, <https://doi.org/10.1016/j.foodhyd.2023.108921>.
5. Nuță, D., Trandafir, V., Godeanu, M., Radu, F., Radu, M., Brad, I., Niță, O., Obtaining Active Biocompounds and Testing Them in Cosmetic Products (in Romanian), *Revista Societății Române de Cosmetică și Chimie*, **2003**, III, 4, 20.
6. Saibaba, K.N., Next Generation Biosurfactants and Their Practical Application in the Food Sector, in Inamuddin and C.O. Adetunji (eds.), *Applications of Next Generation Biosurfactants in the Food Sector*, **2022**, 349–360, <https://doi.org/10.1016/B978-0-12-824283-4.00011-3>.
7. Paun, G., Neagu, E., Alecu, A., Albu, C., Seciu-Grama, A.-M., Radu, G.L., Antioxidant and Antidiabetic Activity of *Cornus mas* L. and *Crataegus monogyna* Fruit Extracts, *Molecules*, **2024**, 29, 3595, <https://doi.org/10.3390/molecules29020326>.
8. Neagu, E., Paun, G., Albu, C., Apreutesei, O.T., Radu, G.L., *In Vitro* Assessment of the Antidiabetic and Anti-Inflammatory Potential of *Artemisia absinthium*, *Artemisia vulgaris* and *Trigonella foenum-graecum* Extracts Processed Using Membrane Technologies, *Molecules*, **2023**, 28, 7156, <https://doi.org/10.3390/molecules28207156>.
9. Paun, G., Neagu, E., Albu, C., Savin, S., Radu, G.L., *In Vitro* Evaluation of Antidiabetic and Anti-Inflammatory Activities of Polyphenolic-Rich Extracts from *Anchusa officinalis* and *Melilotus officinalis*, *ACS Omega*, **2020**, 5, 22, 13014–13022, <https://doi.org/10.1021/acsomega.0c00929>.
10. Paun, G., Neagu, E., Moroeanu, V., Albu, C., Savin, S., Radu, G.L., Chemical and Bioactivity Evaluation of *Eryngium planum* and *Cnicus benedictus* Polyphenolic-Rich Extracts, *BioMed Research International*, **2019**, Article ID 3692605, <https://doi.org/10.1155/2019/3692605>.

# INTEGRATION OF INNOVATIVE TECHNOLOGIES IN VARIOUS STAGES OF FOOTWEAR DESIGN AND MANUFACTURING

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Received: 04.05.2026

Accepted: 18.06.2026

<https://doi.org/10.24264/lfj.26.2.3>

## INTEGRATION OF INNOVATIVE TECHNOLOGIES IN VARIOUS STAGES OF FOOTWEAR DESIGN AND MANUFACTURING

**ABSTRACT.** The article analyzes process innovation in the footwear industry through the integration of digital technologies and additive manufacturing, with the aim of streamlining production and promoting sustainability. The paper documents the transition from traditional methods to an innovative workflow, which begins with concept sketches and continues with parametric design in Rhinoceros software. A central aspect is the ecological approach, through the proposal of biocomposites based on thermoplastic polymers and natural fiber waste, compatible with FDM 3D printing technology. The practical results of the research include the development of 10 concept sketches and the digital design of 17 component elements, including six sole models, six heel models, and five complete shoe models (upper and sole assembly). It is concluded that this synergy between 3D scanning, computational design, and sustainable materials enables enhanced customization and a significant reduction in production time, offering advanced solutions for the niche industry and the circular economy. The objectives of this paper are to document and clarify aspects of footwear design and manufacturing through the use of new technologies.

**KEYWORDS:** footwear, concept sketches, design, 3D printing

## INTEGRAREA TEHNOLOGIILOR INOVATOARE ÎN DIVERSE ETAPE ALE PROIECTĂRII ȘI FABRICAȚIEI DE ÎNCĂLȚĂMINTE

**REZUMAT.** Articolul analizează inovarea proceselor din industria de încălțăminte prin integrarea tehnologiilor digitale și a fabricării aditive, vizând eficientizarea producției și promovarea sustenabilității. Lucrarea documentează trecerea de la metodele tradiționale la un flux de lucru inovator, ce pornește de la schițe de concept și continuă cu proiectarea parametrică în software-ul Rhinoceros. Un aspect central îl reprezintă abordarea ecologică, prin propunerea unor biocompozite pe bază de polimeri termoplastici și deșeuri de fibre naturale, compatibile cu tehnologia de imprimare 3D prin metoda FDM. Rezultatele practice ale cercetării includ elaborarea a 10 schițe concept și proiectarea digitală a 17 elemente componente, printre care se numără șase modele de tălpi, șase modele de tocuri și cinci modele complete de încălțăminte (ansamblu față și talpă). Se concluzionează că această sinergie între scanare 3D, design computațional și materiale sustenabile permite o personalizare accentuată și o reducere semnificativă a timpului de execuție, oferind soluții avansate pentru industria de nișă și economia circulară. Obiectivele lucrării sunt documentarea și clarificarea aspectelor privind proiectarea și fabricarea încălțăminte prin utilizarea noilor tehnologii.

**CUVINTE CHEIE:** incaltaminte, schite de idee, proiectare, imprimare 3D

## INTÉGRATION DE TECHNOLOGIES INNOVANTES AUX DIFFÉRENTES ÉTAPES DE LA CONCEPTION ET DE LA FABRICATION DE CHAUSSURES

**RÉSUMÉ.** Cet article analyse l'innovation des processus dans l'industrie de la chaussure grâce à l'intégration des technologies numériques et de la fabrication additive, dans le but d'optimiser la production et de promouvoir la durabilité. Il documente la transition des méthodes traditionnelles vers un flux de travail innovant, qui commence par des esquisses conceptuelles et se poursuit par la conception paramétrique dans le logiciel Rhinoceros. Un aspect central est l'approche écologique, à travers la proposition de biocomposites à base de polymères thermoplastiques et de déchets de fibres naturelles, compatibles avec la technologie d'impression 3D par la méthode FDM. Les résultats concrets de la recherche comprennent l'élaboration de 10 esquisses conceptuelles et la conception numérique de 17 éléments composants, parmi lesquels figurent six modèles de semelles, six modèles de talons et cinq modèles complets de chaussures (ensemble tige et semelle). Il est conclu que cette synergie entre la numérisation 3D, la conception assistée par ordinateur et les matériaux durables permet une personnalisation accrue et une réduction significative des délais de fabrication, offrant des solutions avancées pour l'industrie de niche et l'économie circulaire. Les objectifs de ce travail sont de documenter et de clarifier les aspects liés à la conception et à la fabrication de chaussures grâce à l'utilisation des nouvelles technologies.

**MOTS-CLÉS :** chaussures, esquisses conceptuelles, conception, impression 3D

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## INTRODUCTION

The current landscape of the footwear industry is marked by an accelerated transition toward digitalization, where the integration of innovative technologies is becoming the cornerstone of footwear manufacturing. The use of parametric design and emerging technologies opens new horizons in the optimization of complex geometries, enabling the development of products that meet consumers' individual needs. The need to reduce production times, operational costs, and raw material consumption, alongside sustainable waste management, necessitates moving away from conventional methods in favor of modern, digitized manufacturing processes.

The evolution of consumer preferences, with a desire for greater customization and active involvement in product configuration, has led to a profound shift in design practices. While traditional methodologies have long ensured production stability, their limitations in terms of adaptability are giving way to algorithmic design [1]. This new paradigm not only overcomes the geometric barriers of classic forms but also maximizes the potential of cutting-edge technologies, offering solutions tailored to the user's physical and morphological characteristics (precise dimensions, ergonomics, aesthetic options).

3D scanning plays a significant role in customizing footwear by accurately capturing the anthropometric characteristics of the user's foot. The data obtained allows the product's geometry to be adapted to the individual dimensions and characteristics of the foot, reducing pressure points and improving load distribution during walking. Compared to systems based on standardized sizes, this approach leads to a better fit, increased comfort, and improved ergonomics, reducing the risk of discomfort or deformities caused by ill-fitting footwear. Integrating 3D scanning data into the digital design process thus enables the development of customized products tailored to the functional and anatomical needs of each user.

The future of footwear development is defined by the synergy between 3D scanning,

digital knitting, sensor technology, and 3D printing [2–8]. 3D printing, in particular, facilitates the production of highly complex structures that are impossible to create using traditional methods such as casting, while also ensuring greater automation and increased cost-effectiveness [2–5]. Complementarily, 3D scanning enables the precise digitization of anthropometric data, which is essential for customized design, reducing human error and providing virtual models that can be validated through durability simulations as early as the design phase [8].

In footwear production, the traditional manufacturing process consists mainly of design, pattern making, cutting, sewing, and sole attachment and finishing. The entire production process is time-consuming and highly complex. Combining 3D modeling technology with 3D printing technology can rapidly produce footwear, thereby reducing time and enhancing the competitiveness of footwear companies [9–11].

The use of 3D software and technology for footwear modeling allows for the creation and modification of footwear shapes in accordance with design requirements. Some products have complex shapes, and 3D modeling technology can be used to improve their design. 3D modeling technology is necessary to integrate fashion elements more quickly and effectively [12, 13].

Thus, processing technology appears to play a significant role in footwear production in modern society and is a realistic and important driving force in its development and advancement, capable of effectively propelling the footwear industry forward.

The main objectives of this scientific paper are to document and clarify aspects related to the design and manufacture of footwear using new technologies.

## EXPERIMENTAL

### Materials and Methods

Product design methodology is defined as the steps followed by a designer or design team to create a new product [14]. Aesthetics and ergonomics begin to take shape during

these stages and continue through the end of the process [15].

Proper management and execution of the initial stages play a crucial role, as they save time and resources and yield improved solutions without having to restart the process.

We start with concept sketches; then, in the subsequent stages of the process, the design is carried out using a CAD (Computer-Aided Design) system; finally, a prototype will be created using 3D printing.

Environmental concerns and cost reduction, as well as the implementation of circular economy and bioeconomy principles, etc., for the sustainable use of natural resources, have led to the need to develop new generations of materials. Manufacturers of polymer composites are seeking alternatives to optimize and replace traditional products with new ones containing a high proportion of bio-based, recyclable, or compostable materials, in the interest of sustainability and responsible practices.

The materials to be used in 3D printing via the FDM (Fused Deposition Modeling) method are biocomposites based on

thermoplastic polymers (such as TR-SBS, TPU, PLA) and natural fiber waste functionalized through melt blending. The TPU-, PLA-, and TR-SBS-based biocomposites used for FDM printing provide a balance between flexibility, mechanical strength, and low weight. TPU provides elasticity and shock absorption, PLA offers rigidity and dimensional stability, and TR-SBS provides wear resistance and flexibility. The addition of natural fibers helps increase stiffness and reduce material density, resulting in lighter and more sustainable footwear components without compromising functional performance.

## RESULTS AND DISCUSSIONS

### Concept Sketches

Concept sketches are a graphical representation of the product and an essential tool in all phases of the design process and in all its forms.

Ten concept sketches of footwear products were developed (Fig. 1), whose components (soles, heels) can be produced using 3D printing.

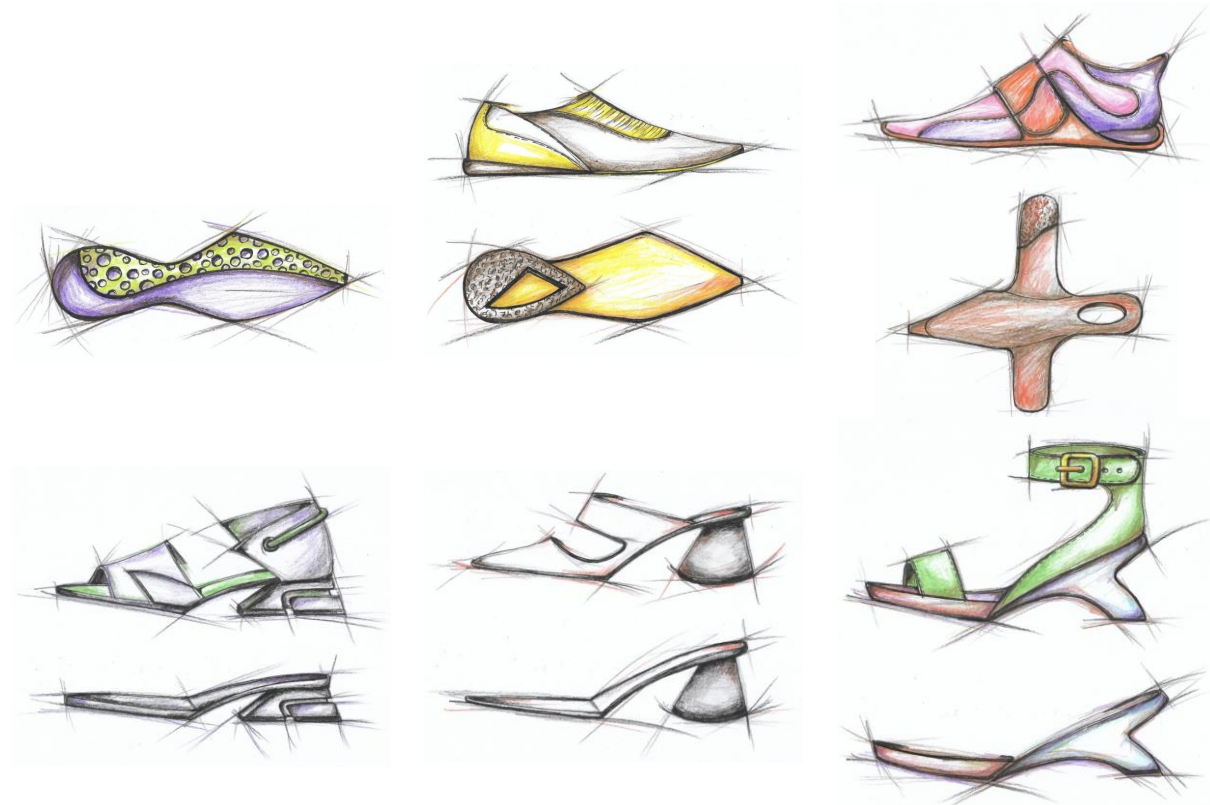






Figure 1. Concept sketches of footwear (*Dsg. Traian Foiasi*)

### 3D Design

CAD/CAM systems represent the new generation of computer-aided design and engineering solutions in the footwear industry. Starting from a last model, a complete footwear model can be quickly created in any combination of colors or textures. The result is a realistic 3D visualization of the product, ideal for presentations to buyers and manufacturers.

Computational design uses algorithms and computational tools to optimize design processes, facilitating rapid prototyping and iteration. By harnessing the power of computation, designers can explore complex design spaces, leading to innovative solutions that might not be feasible using traditional methods alone. Computational design plays a significant role in footwear design, revolutionizing the way shoes are created and manufactured.

Compared to traditional CAD workflows, where modifying geometric parameters typically requires repeated manual interventions on the model, computational design algorithms allow for the

automatic updating of the entire geometry by modifying a small number of variables. This parametric approach significantly reduces the time required for product development and optimization, as the designer can quickly generate and evaluate multiple design variants without having to completely remodel the components. In the case of footwear, algorithms enable the instant adjustment of dimensions, thicknesses, lattice structures, and ergonomic features based on user requirements or data from 3D scans. Furthermore, integrating algorithmic design with digital simulation and 3D printing reduces the number of physical prototypes needed for validation, thereby lowering material consumption and the costs associated with the development process. As a result, efficiency is improved both by shortening design and testing cycles and by increasing flexibility in product customization.

The design of the component elements of the footwear models was carried out using Rhinoceros, a computer graphics and computer-aided design (CAD) software. The software is based on a mathematical model that focuses on producing an accurate

representation of the curves and surfaces of free-form shapes in computer graphics. Rhinoceros can be used for computer-aided design (CAD), computer-aided manufacturing (CAM), rapid prototyping, 3D printing, industrial design (e.g., automotive design, boat design), product design (e.g., footwear design, jewelry design), as well as multimedia and graphic design [16]. Rhinoceros offers

compatibility with other software, as it supports over 30 CAD file formats for import and export [17].

Thus, 17 components of footwear products were designed:

- ✓ six models of flat soles, based on the concept sketches of footwear previously presented (Fig. 2–4);

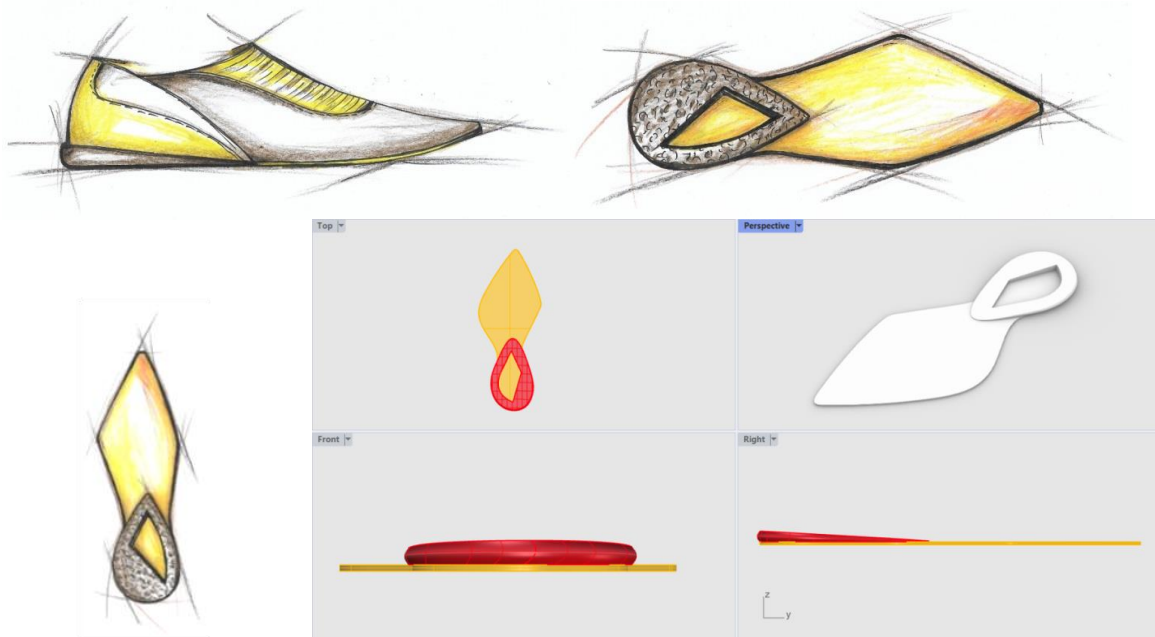


Figure 2. Sole model 1

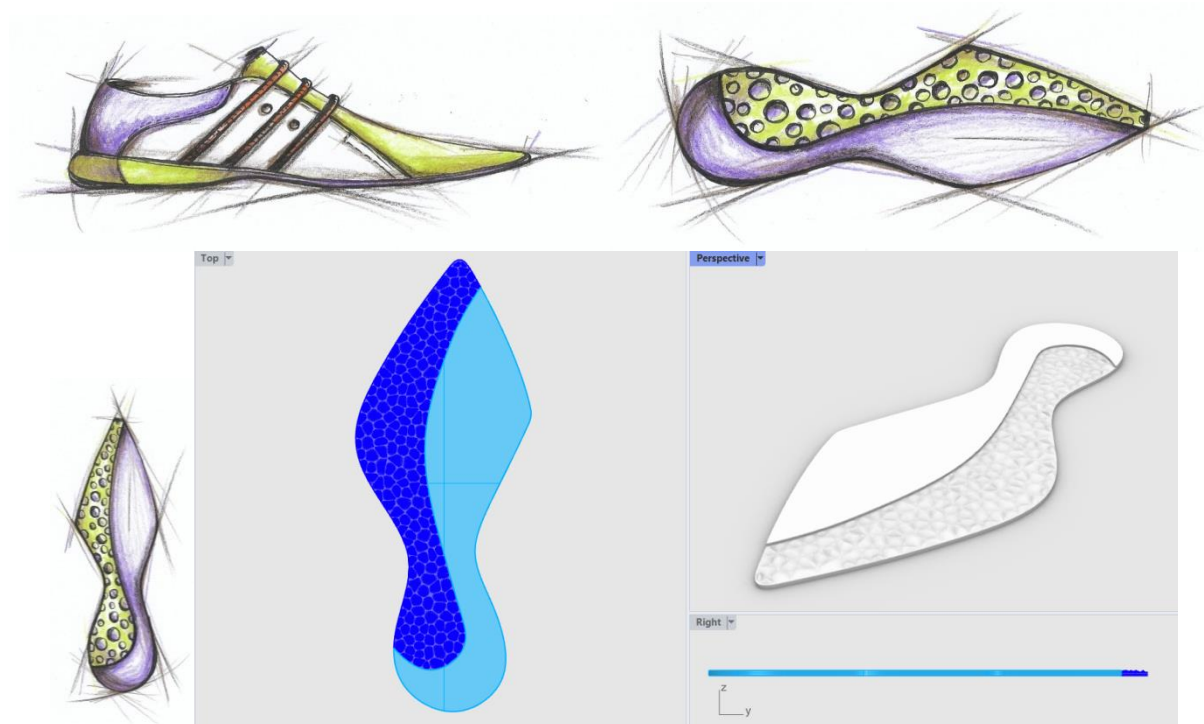


Figure 3. Sole model 2

- ✓ 6 heel models for the designed soles (Fig. 4-5);

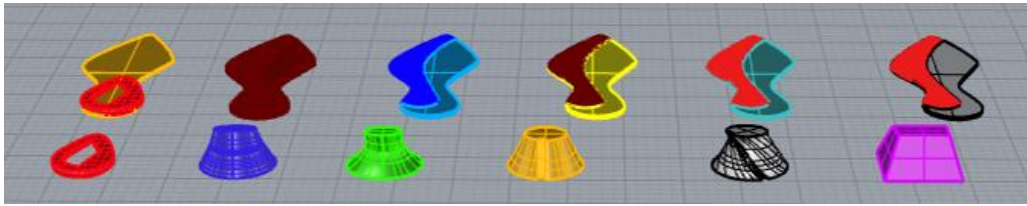


Figure 4. Heel models for the designed soles

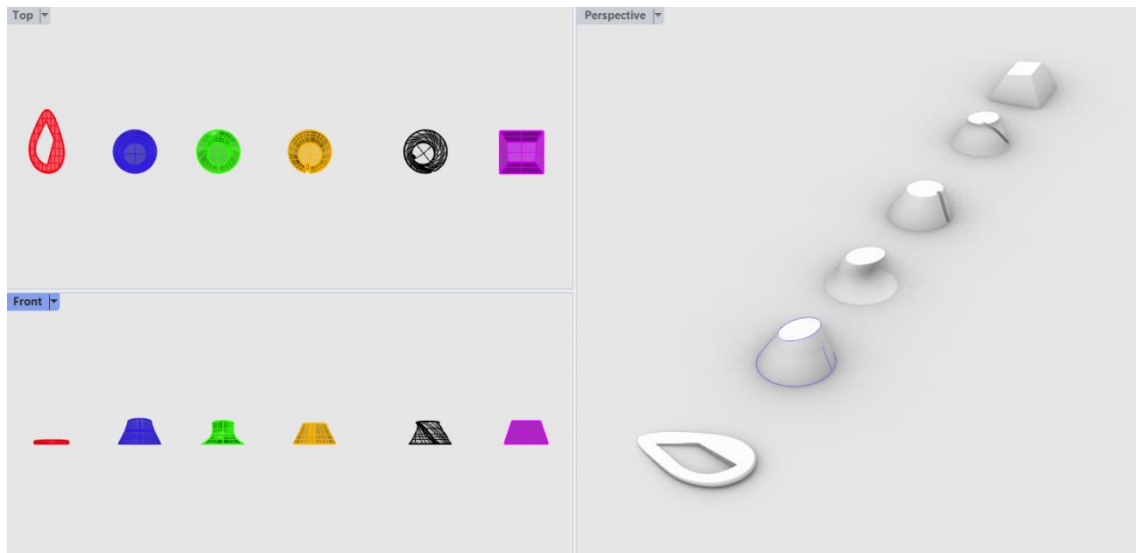


Figure 5. Heel models

- ✓ 5 complete footwear models – upper and sole (two elements) (Fig. 6).



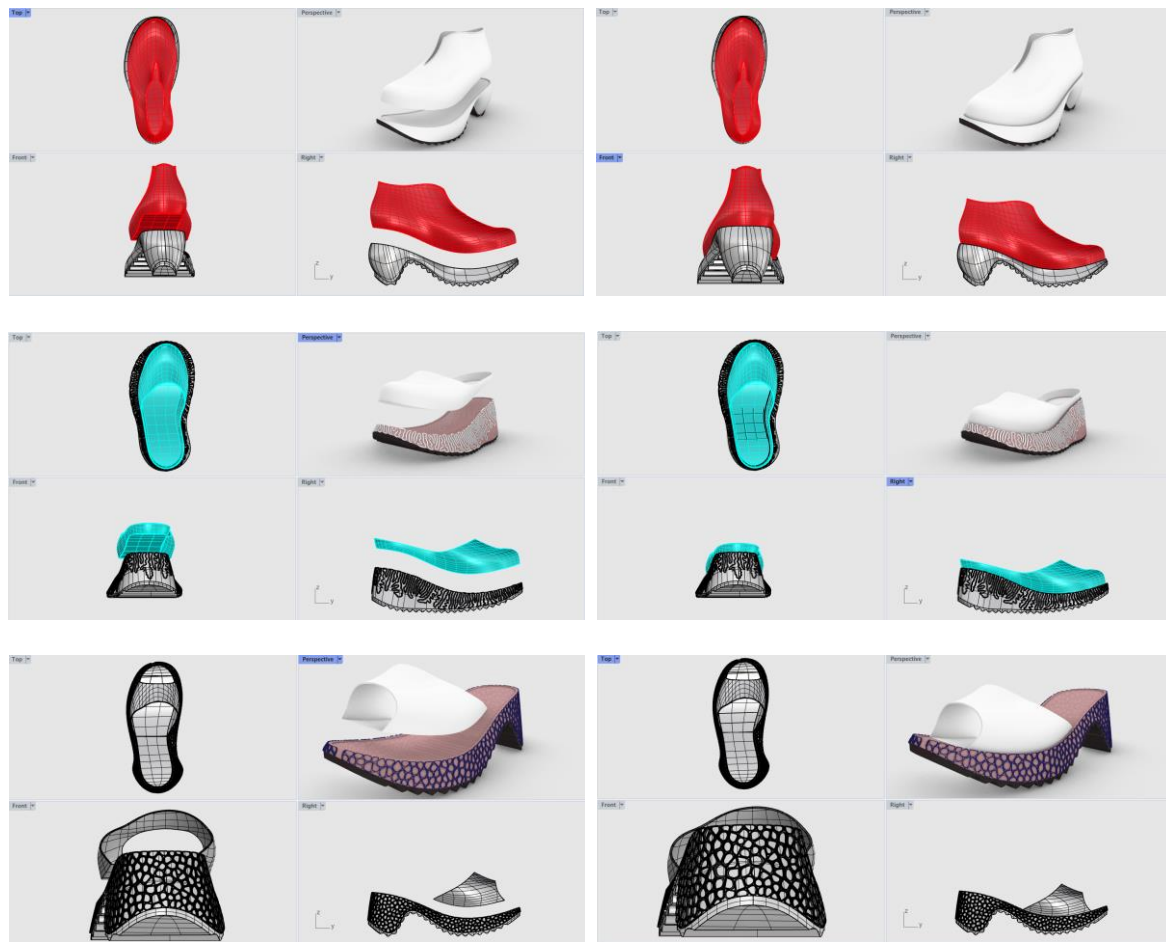


Figure 6. Complete footwear models

### 3D Printing

3D rapid prototyping systems are a revolutionary solution that allows for the creation, within a few hours, of physical three-dimensional objects or models of designed objects directly from 3D CAD/CAM electronic files [18].

Rapid prototyping equipment enables the creation of highly complex samples for verification and validation purposes before a new product is launched into production. Computer-aided 3D printing falls under the category of rapid prototyping technologies and enables the creation of physical prototypes by solidifying successive layers of multi-component powder and bonding them using a liquid binder.

3D printing of footwear using the FDM (Fused Deposition Modeling) method, also known as FFF (Fused Filament Fabrication), is an additive manufacturing process that builds objects layer by layer by extruding a molten

thermoplastic filament. This technology is popular in the industry due to its low costs and the possibility of rapid customization.

Creating a pair of shoes using FDM involves several essential steps [19]:

- Digital Design: Creating a 3D model (CAD file) that may include complex lattice structures to optimize weight and cushioning.
- Slicing: Preparing the model for the printer by converting it into instructions (G-code) that define the print head's path.
- Printing: The filament is heated to a semi-liquid state and deposited in layers onto the print bed.
- Post-processing: Removal of support structures (if necessary), sanding or varnishing of surfaces to achieve a finished appearance.

Fig. 7 shows examples of footwear that can be produced using 3D printing.



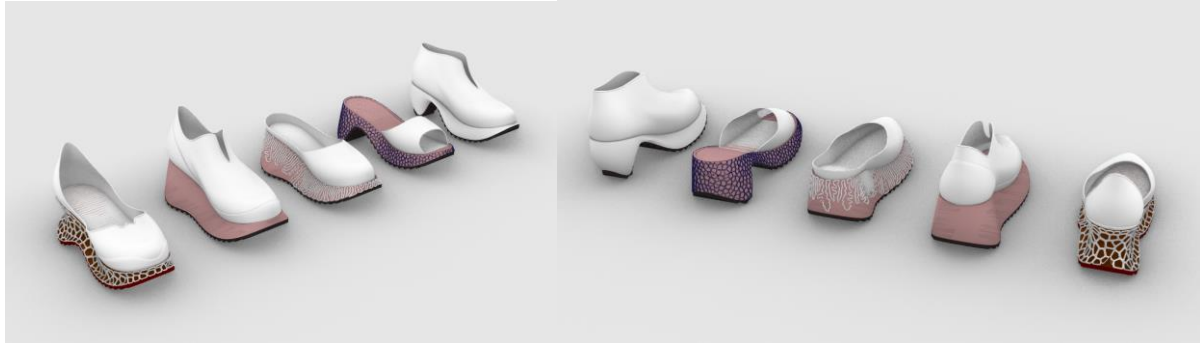


Figure 7. Models that can be produced using 3D printing

### Industrial Scalability and Economic Feasibility

The results obtained in this research demonstrate the potential of integrating digital technologies into a modern workflow for the footwear industry. The development of the 10 concept sketches and the digital design of the 17 components (six sole models, six heel models, and five complete footwear models) highlight the ability of CAD tools to rapidly generate design variants and support iterative product development processes. Compared to conventional methods, where every change requires manual adjustments to drawings and prototypes, using Rhinoceros software allows for rapid model updates and the exploration of a greater number of design solutions in a shorter amount of time.

A key advantage of the proposed workflow is the integration of 3D scanning into the initial design stages. By digitizing the user's anthropometric characteristics, the data obtained can be transferred directly to the CAD environment, facilitating the development of products tailored to the individual characteristics of the foot. In an industrial context, this approach lays the groundwork for implementing production systems geared toward mass customization, in which each product can be adapted to customer requirements without significant changes to the manufacturing infrastructure. Thus, companies can more effectively meet the growing demand for customized products, while maintaining control over costs and delivery times.

Using the Rhinoceros platform also helps increase interoperability between the various stages of the development process.

Compatibility with numerous CAD formats facilitates integration with other software systems used in the industry, reducing the risk of information loss and optimizing data transfer between design, simulation, and manufacturing. This feature is essential for industrial-scale implementation, where collaboration between design, engineering, and manufacturing departments directly influences the efficiency of the product development process.

FDM 3D printing complements this digital workflow by enabling the rapid transformation of virtual models into functional prototypes. Eliminating the need for molds in the early stages of development significantly reduces costs and the time to market for new products. In addition, the technology enables the manufacture of complex geometric structures, including lattice structures designed to optimize weight and comfort, which are difficult or impossible to produce using conventional methods. From an industrial perspective, this flexibility favors small- and medium-scale production, where the high costs of dedicated equipment and manufacturing tools often represent an economic barrier.

The economic feasibility of the workflow is also supported by the use of biocomposites based on thermoplastic polymers and natural fibers. These materials offer the possibility of reducing the consumption of non-renewable resources and recycling waste streams, contributing to the development of production models compatible with the principles of the circular economy. At the same time, additive manufacturing uses material only in the areas

necessary for the product's construction, which leads to a reduction in material waste compared to subtractive processes or traditional manufacturing methods.

Although large-scale implementation requires initial investments in 3D scanning equipment, specialized software, and 3D printing systems, the benefits generated by reduced development time, optimized material consumption, and increased customization can offset these costs in the medium and long term. Consequently, the proposed workflow proves particularly attractive to niche footwear manufacturers, medical and orthopedic applications, as well as companies focused on high-value-added products, where flexibility and adaptability are key competitive advantages.

## CONCLUSIONS

This paper highlights the advantages of integrating innovative digital technologies into the various stages of footwear design and manufacturing, from concept development to prototyping. The proposed workflow, based on concept sketches, 3D scanning, computational design, CAD modeling, and 3D printing, demonstrates the potential for transforming traditional processes into a modern, flexible, and efficient system.

Ten concept sketches were developed, and 17 footwear components were designed, including six sole designs, six heel designs, and five complete footwear designs. The use of Rhinoceros software enabled the rapid development of design variants and the optimization of complex geometries, reducing the time required for design and facilitating product customization according to user requirements. The use of computational design algorithms has made it possible to reduce the number of manual modeling operations and accelerate the iterative product development process, offering a significant advantage over conventional CAD methods based on successive modifications to the geometry.

3D printing using FDM technology enables the rapid production of prototypes and components with complex structures that

are difficult to achieve using conventional methods, reducing the costs and development time associated with new products.

An important aspect of the research is the use of biocomposites based on thermoplastic polymers and natural fibers, which support sustainability goals and the circular economy by utilizing renewable resources and reducing waste. This approach contributes to the development of innovative products with a low environmental impact and performance levels that meet the demands of modern industry.

In conclusion, the synergy between 3D scanning, digital design, and additive manufacturing represents a promising direction for the footwear industry, offering extensive opportunities for customization, process efficiency, and sustainable development. The implementation of these technologies can provide a significant competitive advantage for manufacturers focused on niche products, orthopedic applications, and high-value-added products.

Future research will focus on the construction and experimental testing of the developed prototypes, as well as the evaluation of their mechanical, functional, and ergonomic performance.

## Acknowledgements

This research was financed by the Romanian Ministry of Research, Innovation and Digitalization through Nucleu Program "Multidisciplinary research-development-innovation in the textile-leather field in the vanguard of current societal challenges – TEX-PEL-CHALLENGE 2026", PN 23 26 03 01/2023 project: "Advanced and sustainable polymer biocomposites for the footwear industry and niche areas made according to the principles of the circular economy" - AVANS-COMP-POLYMER.

## REFERENCES

1. Dhokia, V.G., Newman, S.T., Crabtree, P., Ansell, M.P., A Methodology for the Determination of Foamed Polymer Contraction Rates as a Result of Cryogenic CNC Machining, *Robot Comput Integr Manuf*, **2012**, 26, 665–670, <https://doi.org/10.1016/j.rcim.2010.08.003>.

2. Rivera, M.L., Moukperian, M., Ashbrook, D., Mankoff, J., Hudson, S.E., Stretching the Bounds of 3D Printing with Embedded Textiles, Proceedings of the Conference on Human Factors in Computing Systems, Denver Colorado, CO, USA, 6–11 May 2017, Association for Computing Machinery: New York, NY, USA, **2017**, 497–508, <https://doi.org/10.1145/3025453.3025460>.
3. Sabantina, L., Kinzel, F., Ehrmann, A., Finsterbusch, K., Combining 3D Printed Forms with Textile Structures—Mechanical and Geometrical Properties of Multi-Material Systems, Proceedings of the IOP Conference Series: Materials Science and Engineering, Beijing, China, 16–18 May 2015, Institute of Physics Publishing: Beijing, China, **2015**, Vol. 87, <https://doi.org/10.1088/1757-899X/87/1/012005>.
4. Melnikova, R., Ehrmann, A., Finsterbusch, K., 3D Printing of Textile-Based Structures by Fused Deposition Modelling (FDM) with Different Polymer Materials, Proceedings of the IOP Conference Series: Materials Science and Engineering, Ningbo, China, 27–29 May 2014, Institute of Physics Publishing: Bristol, UK, **2014**, Vol. 62, <https://doi.org/10.1088/1757-899X/62/1/012018>.
5. Lu, L., Sharf, A., Zhao, H., Wei, Y., Fan, Q., Chen, X., Savoye, Y., Tu, C., Cohen-Or, D., Chen, B., Build-to-Last: Strength to Weight 3D Printed Objects, *ACM Trans Graph*, **2014**, 33, 4, 1–10, <https://doi.org/10.1145/2601097.2601168>.
6. Firtikiadis, L., Minaoglou, P., Efkolidis, N., Kyratsis, P., Slipper-sole Computational Design: A Customer-based Approach, Proceedings of the VI International Scientific Conference in Contemporary Trends Innovations in the Textile Industry, Belgrade, Serbia, 14–15 September **2023**.
7. Davia-Aracil, M., Hinojo-Pérez, J.J., Jimeno-Morenilla, A., Mora-Mora, H., 3D Printing of Functional Anatomical Insoles, *Comput Ind*, **2018**, 95, 38–53, <https://doi.org/10.1016/j.compind.2017.12.001>.
8. Sarghie, B., Costea, M., Liute, D., Anthropometric Study of the Foot Using 3D Scanning Method and Statistical Analysis, International Symposium in Knitting and Apparel, ISKA 2013, Textiles of the Future, 21–22 June, **2013**, Iasi, Romania, 428–433.
9. Clarke, T.E., Frederick, E.C., Hamill, C.L., The Effects of Shoe Design Parameters on Rearfoot Control in Running, *Med Sci Sports Exerc*, **1983**, 15, 5, 376–381, <https://doi.org/10.1249/00005768-198315050-00006>.
10. Backes, E.H., Pires, L.D.N., Beatrice, C.A.G., Costa, L.C., Passador, F.R., Pessan, L.A., Fabrication of Biocompatible Composites of Poly(lactic acid)/Hydroxyapatite Envisioning Medical Applications, *Polym Eng Sci*, **2020**, 60, 3, 636–644, <https://doi.org/10.1002/pen.25322>.
11. Chantelau, E., Gede, A., Foot Dimensions of Elderly People with and without *Diabetes mellitus* – A Data Basis for Shoe Design, *Gerontology*, **2002**, 48, 4, 241–244, <https://doi.org/10.1159/000058357>.
12. Daneshmand, A., Hashemi, B.H., Performance of Intermediate and Long Links in Eccentrically Braced Frames, *J Constr Steel Res*, **2012**, 70, 167–176, <https://doi.org/10.1016/j.jcsr.2011.10.011>.
13. Hennig, E.M., Sterzing, T., The Influence of Soccer Shoe Design on Playing Performance: A Series of Biomechanical Studies, *Footwear Sci*, **2010**, 2, 1, 3–11, <https://doi.org/10.1080/19424281003691999>.
14. Minaoglou, P., Tzotzis, A., Efkolidis, N., Kyratsis, P., Integrating Artificial Intelligence into the Shoe Design Process, *Eng Proc*, **2024**, 72, 1, 7, <https://doi.org/10.3390/engproc2024072007>.
15. Roberts, J.C., Headleand, C., Ritsos, P.D., Sketching Designs Using the Five Design-Sheet Methodology, *IEEE Trans Vis Comput Graph*, **2015**, 22, 1, 419–428, <https://doi.org/10.1109/TVCG.2015.2467271>.
16. NOVEDGE, *Rhino 3D 6 for Windows and Mac*, **2020**.
17. Rhinoceros Help, Index of Import/Export File Types, **2020**, available from: [https://docs.mcneel.com/rhino/8/help/en-us/fileio/index\\_of\\_import\\_export\\_file\\_types.htm](https://docs.mcneel.com/rhino/8/help/en-us/fileio/index_of_import_export_file_types.htm).
18. Sescioreanu, I., *Technomarket*, **2008**, April-May, 66–67.
19. COTU, FDM (Fused Deposition Modeling), **2024**, available from: <https://www.cotu.cz/en/blog/136/fdm-fused-deposition-modeling>.

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# COMPARATIVE PHYSICO-CHEMICAL ANALYSIS OF INDIGENOUS TRADITIONAL TANNED COWHIDE AND MODERN VEGETABLE-TANNED LEATHER IN THE AMHARA REGION, ETHIOPIA

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Received: 11.03.2026

Accepted: 17.06.2026

<https://doi.org/10.24264/lfj.26.2.4>

## COMPARATIVE PHYSICO-CHEMICAL ANALYSIS OF INDIGENOUS TRADITIONAL TANNED COWHIDE AND MODERN VEGETABLE-TANNED LEATHER IN THE AMHARA REGION, ETHIOPIA

**ABSTRACT.** Despite modern methods being the primary way of producing leather (making up 80-90% of production), there are concerns about the environmental impact of using harmful chemicals like chrome. This study aims to investigate a potential alternative: the indigenous tanning method used in the Amhara region of Ethiopia. The study compares this indigenous method to modern vegetable tanning, assessing the physical and chemical properties of the leather produced, particularly in terms of environmental impact and potential advantages. The goal is to determine whether the eco-friendly nature of the indigenous method gives it a competitive advantage, even if there are differences in the properties of the leather produced. Both unhaired and hair-on indigenous tanned leathers were analyzed and compared with modern vegetable-tanned leather in terms of thickness, tensile strength, tear strength, water absorption, shrinkage temperature, pH, and Fourier Transform Infrared Spectroscopy (FTIR). The study revealed significant differences in physical and chemical properties between unhaired indigenous tanned cowhide leather and hair-on indigenous tanned leather, with modern vegetable-tanned leather being the superior option. Unhaired leather measures 1.32mm, while hair-on leather has a thickness of 1.58mm, both exceeding the recommended minimum value of >0.5mm. The tensile strength of unhaired indigenous cowhide hide leather is 9.62 N/mm<sup>2</sup>, below the recommended value of modern vegetable-tanned leather (>12 N/mm<sup>2</sup>), while hair-on leather has a tensile strength of 13.41 N/mm<sup>2</sup>. Unhaired indigenous cowhide leather has a higher elongation of 32.13% compared to that of hair-on leather, of 12.47%, neither meeting the recommended (>40%) elongation for vegetable-tanned leather. Unhaired and hair-on indigenous cowhide leathers have a tear strength of 80.33 N and 93.67 N, respectively, both meeting the minimum recommended value of modern vegetable-tanned leather (>20 N). Water absorption of unhaired and hair-on indigenous cowhide leathers is 207.47% and 235.50%, respectively, but do not fulfill the minimum recommended value of modern vegetable-tanned leather after 2 hours (<35%). Traditional cowhide leather, with unhaired and hair-on options, has a shrinkage temperature of 54°C and 50.33°C, respectively. The pH of unhaired indigenous cowhide leather is 6.1, while hair-on indigenous cowhide leather is 6.6. In FTIR tests, unhaired indigenous cowhide leathers have fewer single and double bonds, while hair-on indigenous cowhide leathers have more single, double, and triple bonds and fingerprints. The indigenous tanning method is a more environmentally friendly alternative to the modern vegetable tanning method. The study found that the indigenous tanning method produced leather that was comparable in quality to the modern vegetable tanning method. This suggests that the indigenous tanning method could be a viable alternative to the modern vegetable tanning method, especially in areas where environmental concerns are a priority.

**KEYWORDS:** indigenous tanning method, cow hides, physico-chemical properties, modern vegetable tanning

## ANALIZĂ FIZICO-CHIMICĂ COMPARATIVĂ ÎNTRE PIELEA BOVINĂ TĂBĂCITĂ TRADIȚIONAL ȘI PIELEA TĂBĂCITĂ VEGETAL UTILIZÂND METODE MODERNE, ÎN REGIUNEA AMHARA, ETIOPIA

**REZUMAT.** Deși metodele moderne reprezintă principală modalitate de fabricare a pielii (reprezentând 80-90% din producție), există îngrijorări cu privire la impactul asupra mediului al utilizării substanțelor chimice nocive, precum cromul. Prezentul studiu își propune să investigheze o potențială alternativă: metoda tradițională de tăbăcire utilizată în regiunea Amhara din Etiopia. Studiul compară această metodă cu tăbăcirea vegetală modernă, evaluând proprietățile fizice și chimice ale pieilor obținute, în special din perspectiva impactului asupra mediului și a avantajelor potențiale. Scopul este de a stabili dacă caracterul ecologic al metodei tradiționale îi conferă un avantaj competitiv, chiar dacă există diferențe în ceea ce privește proprietățile pieilor obținute. Atât pieile tăbăcite tradițional fără păr, cât și cele cu păr, precum și pielea tăbăcită vegetal utilizând metode moderne s-au analizat comparativ în ceea ce privește grosimea, rezistența la rupere, rezistența la sfâșiere, absorbția apei, temperatura de contracție, pH-ul și spectroscopia în infraroșu cu transformată Fourier (FTIR). Studiul a evidențiat diferențe semnificative în ceea ce privește proprietățile fizice și chimice între pielea bovină tăbăcită tradițional, fără păr, și pielea tăbăcită tradițional, cu păr, pielea tăbăcită vegetal utilizând metode moderne fiind opțiunea superioară. Pielea fără păr are o grosime de 1,32 mm, în timp ce pielea cu păr are o grosime de 1,58 mm, ambele depășind valoarea minimă recomandată de >0,5 mm. Rezistența la rupere a pielii bovine fără păr tăbăcite tradițional este de 9,62 N/mm<sup>2</sup>, sub valoarea recomandată pentru pielea tăbăcită vegetal cu tehnici moderne (>12 N/mm<sup>2</sup>), în timp ce pielea cu păr are o rezistență la rupere de 13,41 N/mm<sup>2</sup>. Pielea bovină fără păr tăbăcită tradițional prezintă o alungire mai mare, de 32,13%, comparativ cu cea a pielii cu păr, de 12,47%, care nu îndeplinește cerința recomandată (>40%) pentru pielea tăbăcită vegetal. Atât pielea bovină fără păr tăbăcită tradițional, cât și cea cu păr au o rezistență la rupere de 80,33 N și, respectiv, 93,67 N, îndeplinind valoarea minimă recomandată pentru pielea tăbăcită vegetal cu tehnici moderne (>20 N). Absorbția de apă a pieilor bovine fără păr și cu păr tăbăcite tradițional este de 207,47% și, respectiv, 235,50%, dar nu îndeplinește valoarea minimă recomandată pentru pielea modernă tăbăcită vegetal după 2 ore (<35%). Pielea bovină tăbăcită tradițional, disponibilă atât în varianta fără păr, cât și cu păr, are o temperatură de contracție de 54 °C, respectiv 50,33 °C. pH-ul pieilor bovine fără păr este de 6,1, în timp ce al pieilor bovine cu păr este de 6,6. În urma testelor FTIR, s-a constatat că pieile bovine fără păr tăbăcite tradițional prezintă mai puține legături simple și duble, în timp ce pieile bovine cu păr tăbăcite tradițional prezintă mai multe legături simple, duble și triple, precum și amprente. Metoda tradițională de tăbăcire reprezintă

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o alternativă mai ecologică față de metoda modernă de tăbăcire vegetală. În urma studiului, s-a constatat că metoda tradițională de tăbăcire a generat o piele comparabilă din punct de vedere al calității cu metoda modernă de tăbăcire vegetală. Acest lucru sugerează că metoda indigenă de tăbăcire ar putea constitui o alternativă viabilă la metoda modernă de tăbăcire vegetală, în special în zonele în care preocupările de mediu reprezintă o prioritate.

CUVINTE CHEIE: metodă indigenă de tăbăcire, piei bovine, proprietăți fizico-chimice, tăbăcire vegetală modernă

#### ANALYSE PHYSICO-CHIMIQUE COMPARATIVE DU CUIR BOVIN TANNÉ DE MANIÈRE TRADITIONNELLE ET DU CUIR TANNÉ VÉGÉTAL SELON DES MÉTHODES MODERNES DANS LA RÉGION D'AMHARA, EN ÉTHIOPIE

RÉSUMÉ. Bien que les méthodes modernes constituent le moyen principal de production du cuir (représentant 80 à 90 % de la production), l'utilisation de produits chimiques nocifs tels que le chrome suscite des inquiétudes quant à son impact environnemental. Cette étude vise à examiner une alternative potentielle : la méthode de tannage traditionnelle utilisée dans la région d'Amhara, en Éthiopie. L'étude compare cette méthode traditionnelle au tannage végétal moderne, en évaluant les propriétés physiques et chimiques du cuir obtenu, notamment en termes d'impact environnemental et d'avantages potentiels. L'objectif est de déterminer si le caractère écologique de la méthode traditionnelle lui confère un avantage concurrentiel, même s'il existe des différences dans les propriétés du cuir obtenu. Des cuirs tannés selon la méthode traditionnelle, tant sans poils qu'avec poils, ont été analysés et comparés au cuir au tannage végétal moderne en termes d'épaisseur, de résistance à la traction, de résistance à la déchirure, d'absorption d'eau, de température de rétrécissement, de pH et de spectroscopie infrarouge à transformée de Fourier (FTIR). L'étude a révélé des différences significatives dans les propriétés physiques et chimiques entre le cuir bovin au tannage traditionnel sans poils et le cuir au tannage traditionnel avec poils, le cuir tanné végétal selon des méthodes modernes s'avérant être la meilleure option. Le cuir sans poils mesure 1,32 mm, tandis que le cuir avec poils présente une épaisseur de 1,58 mm ; ces deux valeurs dépassent la valeur minimale recommandée de >0,5 mm. La résistance à la traction du cuir bovin indigène sans poils est de 9,62 N/mm<sup>2</sup>, ce qui est inférieur à la valeur recommandée pour le cuir au tannage végétal moderne (> 12 N/mm<sup>2</sup>), tandis que le cuir avec poils présente une résistance à la traction de 13,41 N/mm<sup>2</sup>. Le cuir bovin indigène sans poils présente un allongement plus élevé (32,13 %) que celui du cuir avec poils (12,47 %), ce qui ne répond pas à la valeur recommandée (> 40 %) d'allongement pour le cuir tanné végétal. Les cuirs bovins indigènes, tant sans poils qu'avec poils, présentent une résistance à la déchirure de 80,33 N et 93,67 N respectivement, ce qui satisfait à la valeur minimale recommandée pour le cuir tanné végétal moderne (> 20 N). L'absorption d'eau des cuirs bovins indigènes sans poils et avec poils est respectivement de 207,47 % et 235,50 %, mais ne répond pas à la valeur minimale recommandée pour les cuirs au tannage végétal moderne après 2 heures (<35 %). Le cuir bovin au tannage traditionnel, disponible en version « sans poils » et « avec poils », présente respectivement une température de rétrécissement de 54 °C et 50,33 °C. Le pH du cuir bovin indigène sans poils est de 6,1, tandis que celui du cuir bovin indigène avec poils est de 6,6. Lors des tests FTIR, les cuirs bovins indigènes sans poils présentent moins de liaisons simples et doubles, tandis que les cuirs bovins indigènes avec poils présentent davantage de liaisons simples, doubles et triples, ainsi que des empreintes. La méthode de tannage indigène constitue une alternative plus respectueuse de l'environnement que la méthode moderne de tannage végétal. L'étude a révélé que la méthode de tannage traditionnelle permettait d'obtenir un cuir dont la qualité était comparable à celle obtenue par la méthode moderne de tannage végétal. Cela suggère que la méthode de tannage traditionnelle pourrait constituer une alternative viable à la méthode moderne de tannage végétal, en particulier dans les régions où les préoccupations environnementales sont une priorité.

MOTS-CLÉS : méthode de tannage traditionnelle, cuir bovin, propriétés physico-chimiques, tannage végétal moderne

## INTRODUCTION

Ethiopia possesses one of the largest livestock populations in Africa, serving as a major source of livelihood for rural communities and an important supply base for the leather industry. The country produces an estimated 2.4 million hides, 10 million sheepskins, and 7.4 million goatskins annually [1]. Ethiopian sheep predominantly produce hair-type skins that are highly valued for their compact fiber structure and superior tensile strength [2]. The leather sector contributes significantly to the national economy through employment generation, value addition, and export earnings.

Tanning is one of the oldest human technologies and involves the chemical stabilization of animal hides and skins to produce leather that is resistant to microbial degradation, moisture, and mechanical wear. Through tanning, collagen fibers are

transformed into a durable, flexible, and functional material suitable for various applications [3]. While modern tanning industries employ advanced machinery, specialized tanning agents, and controlled processing conditions to achieve consistent leather quality, traditional tanning systems continue to play an important role in many developing countries, particularly in rural communities [4].

Ethiopia has a substantial traditional tanning sector, with more than 6,722 households engaged in indigenous leather processing across the Amhara, Tigray, and Oromia regions. Of these, approximately 5,292 traditional tanners are located in the Amhara region alone, processing more than 700,000 hides annually due to the accessibility of raw materials and local market demand [5]. The Amhara region is particularly recognized for its rich cultural heritage and long-standing

indigenous tanning traditions, making it an important area for investigating the characteristics and performance of traditionally processed leather [6].

Traditional tanning practices in the Amhara region rely primarily on locally available botanical resources rather than synthetic tanning chemicals. Indigenous tanners commonly prepare tanning liquors from tannin-rich plant materials obtained from the bark, leaves, roots, fruits, and seed pods of native vegetation, including species of *Acacia*, *Cordia africana*, *Vernonia amygdalina*, and other locally available plants. These materials contain condensed and hydrolysable tannins, which are polyphenolic compounds capable of forming stable cross-links with collagen fibers in animal hides [5]. In addition, animal fats and other organic materials are often used during hide preservation, lubrication, and softening processes. Because these tanning agents are naturally derived and biodegradable, indigenous tanning systems generally generate fewer hazardous chemical residues than conventional chrome tanning processes, which are associated with chromium-containing effluents and environmental concerns [7].

Despite their environmental advantages, traditional leather production systems in the Amhara region face several challenges. The processing activities are often carried out under cottage-industry conditions and may generate unpleasant odors, solid wastes, and gaseous emissions due to limited waste-management practices [8]. Furthermore, traditionally tanned cowhide leather is frequently characterized by non-uniform thickness, heavy weight, limited color variation, lower water resistance, variable surface appearance, and labor-intensive production methods [1]. Additional constraints include low technology adoption, inconsistent raw material quality, limited access to skilled labor, inadequate financial resources, and weak market linkages [9]. According to [10], traditional hide and skin tanning is commonly practiced as a supplementary livelihood activity rather than as a specialized occupation.

Although indigenous tanning remains culturally and economically important in the Amhara region, limited scientific information is

available regarding the physicochemical properties of the resulting leather and how these properties compare with those of modern vegetable-tanned leather. Therefore, this study aimed to evaluate and compare the physicochemical characteristics of indigenous traditional tanned cowhide leather and modern vegetable-tanned leather. The investigation focused on thickness, tensile strength, elongation at break, tear strength, water absorption, shrinkage temperature, pH, and Fourier Transform Infrared Spectroscopy (FTIR) characteristics. The experimental leathers were subjected to physical and chemical analyses, and the obtained results were compared with recommended standards for vegetable-tanned upholstery leather [11]. The findings are expected to provide scientific evidence regarding the quality, performance, and sustainability potential of indigenous tanning practices in the Amhara region of Ethiopia.

## EXPERIMENTAL

### Materials

**Cowhides:** indigenous unhaird and hair-on tanned cowhide were sourced from the Amhara regional state of Bahir Dar city, ensuring similar quality and source.

**Chemical Reagents:** Distilled water, sulfuric acid concentration 98.3%, ammonia concentration 31%, sodium hydroxide solution concentration 50.5%, formic acid 85 %, and pH adjustment in certain reactions and analyses.

### Methods

Using a random selection method, three full unhaird and three full hair-on leather pieces tanned through indigenous tanning method were collected from Amhara region in Bahir Dar city, then prepared for the required testing methods.

### Organoleptic Properties Analysis of Indigenous Tanned Hides

Prior to physical testing, all leather specimens were conditioned according to ISO 2419 under standard atmospheric conditions of  $23 \pm 2$  °C temperature and  $50 \pm 5\%$  relative humidity for a minimum of 48 h.

Table 1: Testing Standards

| Property                        | Standard                            |
|---------------------------------|-------------------------------------|
| Sampling                        | ISO 2418                            |
| Conditioning                    | ISO 2419                            |
| Thickness                       | ISO 2589                            |
| Tensile strength and elongation | ISO 3376                            |
| Tear strength                   | ISO 3377-2                          |
| pH                              | ISO 4045                            |
| Shrinkage temperature           | ISO 3380                            |
| FTIR                            | ASTM E1252 (or instrument protocol) |

### Thickness Test

The samples were tested and analyzed using the machine GT-313A1 thickness gauge with the samples prepared according to ES ISO 2589:2016 for both unhaired and hair-on

indigenous tanned cowhide from the Amhara region of Bahir Dar City. For each type of unhaired and hair-on leather, three samples were taken. Five measurements were taken, distributed across a single sample and the average calculated to guarantee measurement accuracy and consistency.



Figure 1. Thickness measurement

### Tensile Strength Test

Under room conditions, the tensile strength of both hair-on and hair-off indigenous tanned cowhide was measured by using an ASTM D2209 tensile testing machine with ISO 3376. For the physical test of the leather, test pieces were measured and cut

from the sampling point perpendicular to and parallel to the backbone in the desired shape and size. Length A= 140, B= 50, C= 55, D= 20, R= 10; millimeters are used in the measurement. By dividing the breaking force in kilograms-force by the unstretched test piece's cross-section in square millimeters, the tensile strength was computed.



Figure 2. Measuring tensile strength (left); samples from unhaired traditional cowhide leather (center); samples from hair-on traditional cowhide leather (right)

### Elongation

Leather elongation, like any material, is typically measured through a tensile test. This test stretches a sample with a controlled force until it breaks, recording the force and deformation (elongation) throughout the process.

$$\text{Elongation (\%)} = [(L_f - L_i) / L_i] * 100 \quad (1)$$

where:  $L_f$  is the final gauge length of the sample after fracture (mm);  $L_i$  is the initial gauge length of the sample before testing (mm).

### Tear Strength Test

An ASTM D2261 tear strength testing machine fitted with an ISO 3376 was used to measure the tear strength of both hairless and hair-on indigenous tanned cowhide. The test piece, measuring 75mm in length × 25 mm in width, is positioned perpendicularly and parallelly to the backbone of indigenous tanned cowhide leather. A 5 mm diameter hole was created on the midline and 25 mm from one end of each test piece.



Figure 3. Measuring tear strength by ASTM D2261 (left); samples from un-haired traditional cowhide leather (center); samples from hair-on traditional cowhide leather (right)

### Water Absorption

Water absorption in cowhide leather treated through indigenous method was measured using a gravimetric method BS 3144-SLP19 (IUP7), which is a 70mm circular cylinder cut from a glass vessel with a diameter over 80mm. A circular cylinder with a diameter of 70mm is cut from an un-haired and hair-on

indigenously tanned cowhide and kept in a standard atmosphere at 27°C. The test piece is weighed to the nearest 0.01g and immersed in water at 27°C. After 2 hours, the weight is blotted and the percentage of water absorbed is calculated using the formula:

$$Q = 100(w_1 - w_0) / w_0 \quad (2)$$

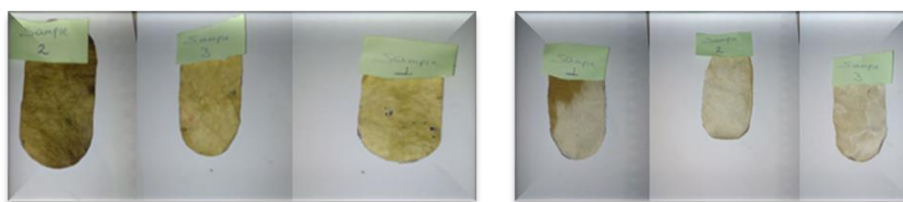


Figure 4. Water absorption test: un-haired traditional cowhide leather (left); samples from un-haired traditional cowhide leather (right)

### Shrinkage Temperature

The shrinkage temperature of an un-haired and hair-on indigenous tanned cowhide strip was determined by using IS: 5914 – 1970. A 50 \* 3 mm rectangle of leather was

cut from a specified location and then immersed in 10 ml of water. When a strip of leather is gradually heated in water, it undergoes sudden shrinkage at a temperature specific to tanning.





Figure 5. Unhaired and hair-on leather samples before shrinkage test, respectively



Figure 6. Unhaired and hair-on leather samples after shrinkage test, respectively

### Chemical Property Analysis of Indigenous Tanned Leather

#### *pH Test*

The acidity and basicity of indigenous tanned leather were determined by using the IS 582[LC:18] – 1970 method. An amount of 5+

0.1 g from the test portion is weighed and taken in a polyethylene flask bottle, and shaken well with 100 ml of water for 30 seconds to wet the ground leather uniformly. Then it was mechanically shaken in the shaker for 16 to 24 hours. The solution was filtered and pH was measured using pH meter HI-99171.



Figure 7. Measuring the pH of traditional unhaired and hair-on cowhide leather

#### *Fourier Transform Infrared Spectroscopy*

The Fourier Transform Infrared Spectroscopy of the leather sample was measured using FTIR machine L1600400 SPECTRA TWO DTGS were used for analyzing the chemical composition and structural characteristics. As per [12], using a scalpel and a sharp blade, the leather samples were

scraped until they became thin. FTIR spectroscopy was used directly to evaluate the samples.

## RESULTS AND DISCUSSION

### Comparative Thickness of Indigenous with Modern Vegetable-Tanned Leather

Table 2 below shows that indigenous tanned cowhide leather with hair-on is thicker than indigenous tanned cowhide leather without hair. Every section of the particular

sample of indigenous tanned cowhide leather has different thicknesses that have been noticed. It indicates that changes in thickness are due to non-uniform filling action of a tanning agent; although the thickness of the indigenous tanned cowhide leather meets the minimum necessary value, it is not consistently thick, according to the statistics below.

Table 2: Comparative thickness of indigenous with modern vegetable tanned leather

| Comparative thickness (mm) value of leather tanned by ITL and MDTL        |          |        |        |         |        |        |
|---------------------------------------------------------------------------|----------|--------|--------|---------|--------|--------|
| Sample                                                                    | Unhaired |        |        | Hair-on |        |        |
|                                                                           | 1        | 2      | 3      | 1       | 2      | 3      |
| ITL                                                                       | 1.17mm   | 1.26mm | 1.54mm | 1.70mm  | 1.57mm | 1.47mm |
| Average                                                                   | 1.32mm   |        |        | 1.58mm  |        |        |
| Minimum recommended thickness value of vegetable-tanned leather (mm) MDTL |          |        |        |         |        | >0.5mm |

Note: ITL - through the indigenous tanning method and MDTL - modern tanned leather

### Tensile Strength of Indigenous Tanned Cowhide Leather

From Table 3 below the tensile strength of indigenous tanned cowhide hide leather without hair is 9.62 N/mm<sup>2</sup>, which is less than

the minimum recommended value of modern vegetable-tanned leather. The tensile strength of traditional cowhide hide leather with hair is 13.41 N/mm<sup>2</sup>, which satisfies the minimum recommended value of modern vegetable-tanned leather >12 N/mm<sup>2</sup>.

Table 3: Tensile strength of indigenous tanned cowhide leather

| Tensile strength (N/mm <sup>2</sup> ) value of leather tanned by ITL and MDTL   |                        |       |      |                         |       |       |
|---------------------------------------------------------------------------------|------------------------|-------|------|-------------------------|-------|-------|
| Sample                                                                          | Unhaired               |       |      | Hair-on                 |       |       |
|                                                                                 | 1                      | 2     | 3    | 1                       | 2     | 3     |
| ITL                                                                             | 9.32                   | 16.77 | 2.77 | 8.93                    | 15.61 | 15.70 |
| Average                                                                         | 9.62 N/mm <sup>2</sup> |       |      | 13.41 N/mm <sup>2</sup> |       |       |
| Minimum recommended value of vegetable-tanned leather (N/mm <sup>2</sup> ) MDTL |                        |       |      |                         |       | >12   |

### Elongation at Break of Indigenous Tanned Cowhide Leather

Based on Table 4 below the elongation of unhaired indigenous tanned cowhide leather is 32.13%, while the elongation of hair-on indigenous cowhide leather is 12.47%. These values come up narrow of the minimum recommended value of vegetable-tanned leather >40%; however, the elongation of unhair indigenous cowhide leather is greater

than that of hair-on indigenous cowhide leather. These findings demonstrate that indigenous tanned cowhide leathers, both hair-on, and hair-off, are more rigid and durable than modern vegetable-tanned leather and more challenging to stretch, wear, and penetrate. These results showed that unhaired and hair-on indigenous cowhide leathers are stiffer and tougher than modern vegetable-tanned leather and difficult to stretch, wear, and penetrate.

Table 4: Elongation at break of indigenous tanned cowhide leather

| Elongation (%) value of leather tanned by ITL and MDTL         |          |       |     |         |       |       |
|----------------------------------------------------------------|----------|-------|-----|---------|-------|-------|
| Sample                                                         | Unhaired |       |     | Hair-on |       |       |
|                                                                | 1        | 2     | 3   | 1       | 2     | 3     |
| ITL                                                            | 31.6%    | 16.8% | 48% | 12%     | 12.8% | 12.6% |
| Average                                                        | 32.13%   |       |     | 12.47%  |       |       |
| Minimum recommended value of vegetable-tanned leather (%) MDTL |          |       |     |         |       | >40%  |

### Tear Strength of Indigenous Tanned Cowhide Leather

The tests and data in Table 5 below show that the tear strengths of typical cowhide leathers, both hair-on and hair-off, are 80.33 N and 93.67 N, respectively. The tear strength of

hair-on indigenous tanned cowhide leather is greater than that of unhaired indigenous tanned cowhide leather. However, the minimum suggested value of vegetable-tanned leather >20N is met by both hair-on and hair-off. These show that classic cowhide leather is robust, stiff, ductile, and sturdy.

Table 5: Tear strength of indigenous tanned cowhide leather

| Tear strength (N) value of leather tanned by ITL and MDTL      |          |    |    |         |     |     |
|----------------------------------------------------------------|----------|----|----|---------|-----|-----|
| Sample                                                         | Unhaired |    |    | Hair-on |     |     |
|                                                                | 1        | 2  | 3  | 1       | 2   | 3   |
| ITL                                                            | 111      | 72 | 58 | 96      | 102 | 83  |
| Average                                                        | 80.33    |    |    | 93.67   |     |     |
| Minimum recommended value of vegetable-tanned leather (N) MDTL |          |    |    |         |     | >20 |

### Water Absorption of Indigenous Tanned Cowhide Leather

The results observed and noted in Table 6 below show that after two hours, the water absorption of indigenous tanned cowhide leathers with and without hair is 207.47% and 235.50%, respectively. However, this does not

meet the minimum suggested value of modern vegetable-tanned leather, which is less than 35%. The finding indicated that indigenous tanned cowhide leathers without hair absorb less water than those with hair, and that traditional tanned cowhide leathers have a higher water absorption capacity than modern vegetable-tanned leather.

Table 6: Water absorption of indigenous tanned cowhide leather

| Water absorption (%) value of leather tanned by ITL and MDTL   |          |        |        |         |        |        |
|----------------------------------------------------------------|----------|--------|--------|---------|--------|--------|
| Sample                                                         | Unhaired |        |        | Hair-on |        |        |
|                                                                | 1        | 2      | 3      | 1       | 2      | 3      |
| ITL                                                            | 141.11   | 215.38 | 265.92 | 144.60  | 253.92 | 308.00 |
| Average                                                        | 207.47   |        |        | 235.50  |        |        |
| Minimum recommended value of vegetable-tanned leather (%) MDTL |          |        |        |         |        | <35%   |

### Shrinkage Temperature of Indigenous Tanned Cowhide Leather

From Table 7 below the shrinkage temperature of indigenous tanned cowhide leather without hair is 54 °C, while the

shrinkage temperature of leather with hair on is 50.33 °C. Traditional tanned cowhide leather does not meet the minimum recommended value of shrinkage temperature, compared to modern vegetable-tanned leather, which has a shrinkage temperature of >60 °C.

Table 7: Shrinkage temperature of indigenous tanned cowhide leather

| Shrinkage temperature (°C) value of leather tanned by ITL and MDTL |          |    |    |          |    |       |
|--------------------------------------------------------------------|----------|----|----|----------|----|-------|
| Sample                                                             | Unhaired |    |    | Hair-on  |    |       |
|                                                                    | 1        | 2  | 3  | 1        | 2  | 3     |
| ITL                                                                | 54       | 57 | 51 | 52       | 49 | 50    |
| Average                                                            | 54 °C    |    |    | 50.33 °C |    |       |
| Minimum recommended value of vegetable-tanned leather (°C) MDTL    |          |    |    |          |    | 60 °C |

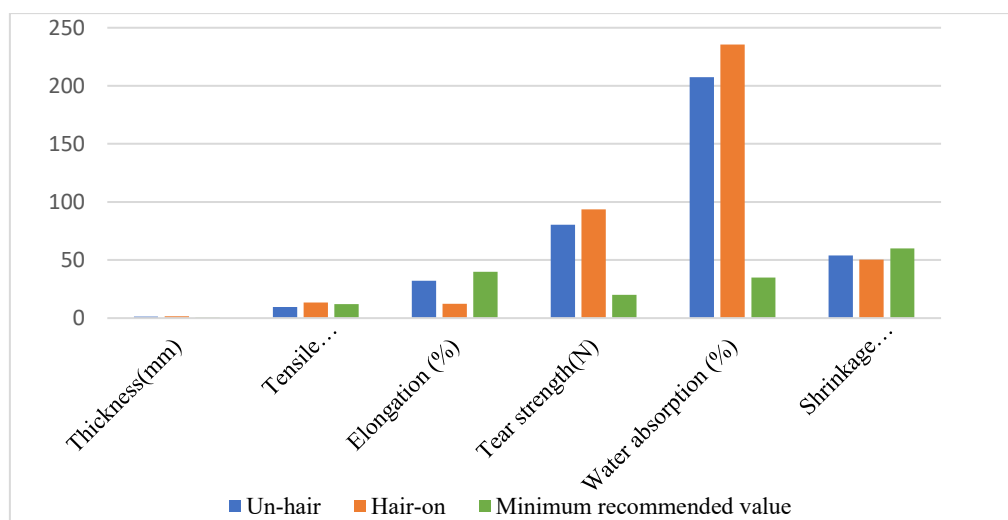


Figure 8. Diagrammatic representation of the physical properties of indigenous cowhides

### pH of Indigenous Tanned Cowhide Leather

Table 8 indicates that the pH of indigenous cowhide leather without hair is 6.1 and that of indigenous tanned cowhide leather with hair is 6.6. These values are within the range of modern vegetable-tanned leather, without falling below 4 and the difference

value not rising above 0.7. It is impossible to say whether tanned leather is better than hair-on indigenous cowhide leather, however, this suggests that unhaired indigenous cowhide leather is superior. According to the pH, indigenous cowhide leather is only tanned up to the point of pickling. Dyeing and fixing the colors is challenging at this pH level.

Table 8: pH of indigenous tanned cowhide leather

| pH value of leather tanned by ITL and MDTL                   |          |     |     |         |                                                   |    |
|--------------------------------------------------------------|----------|-----|-----|---------|---------------------------------------------------|----|
| Sample                                                       | Unhaired |     |     | Hair-on |                                                   |    |
|                                                              | 1        | 2   | 3   | 1       | 2                                                 | 3  |
| ITL                                                          | 6.0      | 6.3 | 6.1 | 52      | 49                                                | 50 |
| Average                                                      |          | 6.1 |     |         | 6.6                                               |    |
| Recommended pH value of modern vegetable-tanned leather MDTL |          |     |     |         | Not below 4.<br>Difference value<br>not above 0.7 |    |

### FTIR Test Result of Traditional Tanned Cowhide Leather

The FTIR spectra of indigenous tanned and modern vegetable-tanned cowhide leathers were analyzed to identify the functional groups associated with collagen structure and tannin–collagen interactions. The spectra were interpreted within four characteristic regions: the single-bond stretching region (2500–4000  $\text{cm}^{-1}$ ), the triple-bond region (2000–2500  $\text{cm}^{-1}$ ), the double-bond region (1500–2000  $\text{cm}^{-1}$ ), and the fingerprint region (600–1500  $\text{cm}^{-1}$ ).

The FTIR spectra of both indigenous and modern vegetable-tanned leathers exhibited characteristic collagen absorption bands. A

broad absorption peak observed within the range of 3200–3400  $\text{cm}^{-1}$  corresponds to O–H and N–H stretching vibrations associated with collagen molecules and phenolic compounds. The presence of absorption bands within 3200–3600  $\text{cm}^{-1}$  indicates hydroxyl groups originating from vegetable tannins, suggesting successful penetration of tannin compounds into the collagen matrix. The absorption band near 1630–1650  $\text{cm}^{-1}$  corresponds to the Amide I region and is attributed mainly to C=O stretching vibrations of collagen peptide bonds. Peaks observed around 1540–1555  $\text{cm}^{-1}$  represent the Amide II band, arising from N–H bending and C–N stretching vibrations. Furthermore, the Amide III region was identified between 1230 and 1300  $\text{cm}^{-1}$ ,



confirming the preservation of the collagen triple-helical structure after tanning. The fingerprint region (600–1500  $\text{cm}^{-1}$ ) contained several characteristic peaks related to collagen and tannin interactions, providing additional evidence of leather stabilization.

Compared with hair-on indigenous tanned cowhide leather and modern vegetable-tanned leather, the FTIR spectrum of unhaired indigenous tanned cowhide leather exhibited fewer peaks and lower absorption intensity within the single-bond, double-bond, triple-bond, and fingerprint regions. This suggests a lower degree of tannin–collagen interaction and a less extensive cross-linking network within the collagen structure. In contrast, hair-on indigenous tanned cowhide leather displayed a greater number of peaks

and stronger absorption bands across these regions, indicating enhanced retention of functional groups and stronger molecular interactions. Differences in peak intensity between unhaired and hair-on indigenous leathers may be attributed to variations in tannin penetration, collagen stabilization, and the preservation of natural structural components during processing.

Overall, the FTIR results confirmed the presence of characteristic collagen amide bands and tannin-related hydroxyl groups in all leather samples. These findings demonstrate that indigenous tanning agents interact with collagen fibers through polyphenolic compounds, although the extent of stabilization appears lower than that observed in modern vegetable-tanned leather.

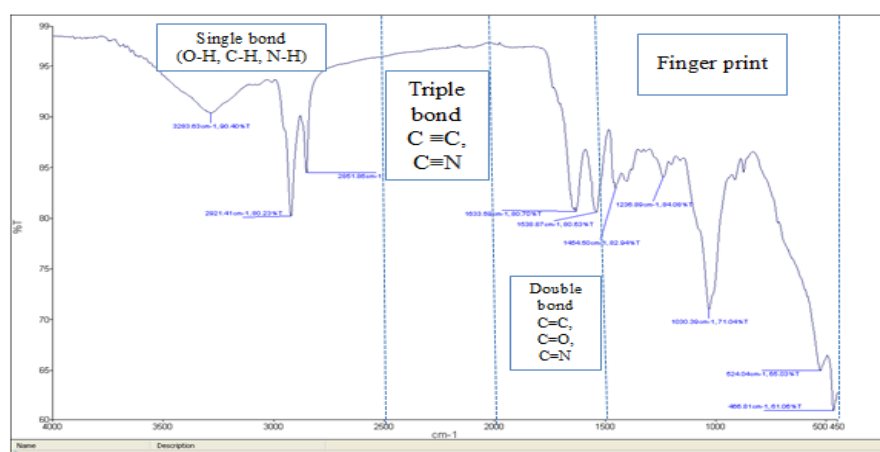


Figure 9. FTIR spectrum of unhaired traditional cowhide leather

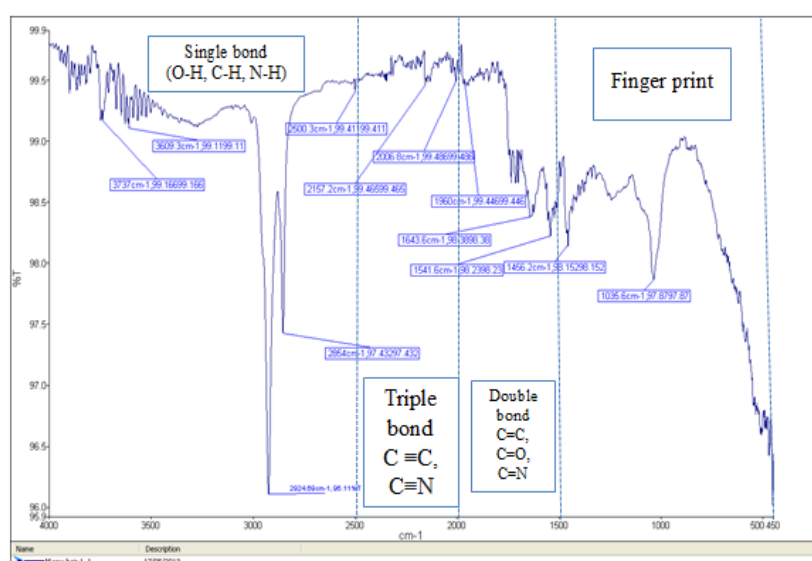


Figure 10. FTIR spectrum of hair-on traditional cowhide leather

## FUTURE WORK

The author acknowledges the importance of Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), and water absorption kinetic studies. However, these analyses require specialized instrumentation that was not available during the present investigation. The recommendation has been incorporated into the Future Research section, where these techniques are proposed for further evaluation of thermal stability, cross-linking density, and moisture diffusion behavior of indigenous tanned leathers.

## CONCLUSION

This study compared the physicochemical properties of unhaired indigenous tanned cowhide leather, hair-on indigenous tanned cowhide leather, and modern vegetable-tanned leather. The results revealed significant differences in the physical, chemical, and structural characteristics of the leather samples. The thickness values of unhaired and hair-on indigenous tanned leathers were 1.32 mm and 1.58 mm, respectively, exceeding the minimum recommended value for vegetable-tanned leather (>0.5 mm). Hair-on indigenous leather exhibited a tensile strength of 13.41 N/mm<sup>2</sup>, satisfying the recommended minimum value (>12 N/mm<sup>2</sup>), whereas unhaired indigenous leather showed a lower tensile strength of 9.62 N/mm<sup>2</sup>. The elongation at break values of both indigenous leathers (32.13% for unhaired and 12.47% for hair-on) were below the recommended value for vegetable-tanned leather (>40%).

Both unhaired and hair-on indigenous leathers demonstrated excellent tear strength values of 80.33 N and 93.67 N, respectively, considerably exceeding the minimum recommended value of 20 N. However, water absorption values were exceptionally high, reaching 207.47% for unhaired leather and 235.50% for hair-on leather after 2 h of immersion, indicating poor moisture resistance compared with modern vegetable-tanned leather (<35%). Similarly, the shrinkage temperatures of unhaired (54 °C) and hair-on

(50.33 °C) indigenous leathers were lower than the recommended value for vegetable-tanned leather (>60 °C), suggesting lower hydrothermal stability and weaker collagen cross-linking. The pH values of both indigenous leathers (6.1 and 6.6) were within the acceptable range for leather materials.

FTIR analysis confirmed the presence of characteristic collagen absorption bands, including Amide I, Amide II, and Amide III, together with hydroxyl groups associated with vegetable tannins. Differences in peak intensity between unhaired and hair-on indigenous leathers indicated variations in tannin penetration and collagen stabilization. Hair-on indigenous leather exhibited stronger absorption bands and a greater number of spectral peaks, suggesting more extensive molecular interactions within the collagen matrix.

Overall, modern vegetable-tanned leather demonstrated superior tensile strength, elongation, hydrothermal stability, and moisture resistance. Nevertheless, indigenous tanned leathers exhibited acceptable thickness, tear strength, and near-neutral pH characteristics while utilizing locally available, biodegradable botanical tanning resources. Therefore, indigenous tanning represents a potentially sustainable and environmentally friendly alternative for traditional applications and selected low-performance leather products. Further studies employing advanced characterization techniques such as Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), and water absorption kinetics are recommended to better understand the thermal stability, cross-linking behavior, and moisture transport mechanisms of indigenous tanned leathers.

## Acknowledgments

The author would like to acknowledge the Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University, for the laboratory facilities support in the successful completion of the research work. The author would also like to thank the Ethiopian Leather Industry Development Institute and Bahir Dar

Tannery for the laboratory facilities and chemical support.

## REFERENCES

1. Adem, M., Production of Hide and Skin in Ethiopia; Marketing Opportunities and Constraints: A Review Paper, *Cogent Food Agric*, **2019**, 5, 1, 1565078, <https://doi.org/10.1080/23311932.2019.1565078>.
2. Bediye Negese, D., Evaluation of Morphological Differences, Structural Indices of Arsi-Bale Sheep Breed and Breeding Practices of the Communities in Selected Districts of Arsi and Bale Zones, Oromia, Ethiopia, Masters' Thesis, Haramaya University, **2020**.
3. Sai Bhavya, K., Raji, P., Selvarani, A.J., Samrot, A.V., Mohamed Javad, P.T., Appalaraju, V.V.S.S., Leather Processing, Its Effects on Environment and Alternatives of Chrome Tanning, *Int J Adv Res Eng Technol*, **2019**, 10, 6, <https://doi.org/10.34218/IJARET.10.6.2019.009>.
4. Yizengaw, M.A., Birlie, A.A., Tesfaye, T., Katrikan, R., Cheklie, E.B., Girma, Z., Grape Waste as Leather-Like Material Alternative: A Comprehensive Review of Ancient Practices, Current Technologies, and Future Trends, *J Renew Mater*, **2026**, 14, 5, <https://doi.org/10.32604/jrm.2025.02025-0175>.
5. Gebremichael, B., Traditional Leather Processing, Production and Marketing in Amhara Regional State of Ethiopia, *Open Access Library Journal*, **2016**, 3, 12, 1-17, <https://doi.org/10.4236/oalib.1102751>.
6. Amde, B., Assessment of Pre-and Post Slaughter Hide and Skin Defects and Their Association with Carcass Condemnation in Two Woredas of East Arsi Zone, Ethiopia, Master's Thesis, Addis Ababa University, College of Veterinary Medicine and Agriculture, **2015**.
7. John Unango, F., Duraisamy, R., Ramasamy, K.M., Birhanu, T., Characteristics and Tanning Potential of *Hagenia abyssinica* Tannin Extracts and Its Possible Use in Clean Leather Production, *Cogent Eng*, **2021**, 8, 1, 1993520, <https://doi.org/10.1080/23311916.2021.1993520>.
8. Saran, S., Chib, S., Saxena, R.K., Biotechnology of Leather: An Alternative to Conventional Leather Processing, in Saran, S., Babu, V., Chaubey, A. (eds.), *High Value Fermentation Products: Human Welfare*, **2019**, 23-47, <https://doi.org/10.1002/9781119555384.ch2>.
9. Grumiller, J., Raza, W.G., The Ethiopian Leather and Leather Products Sector: An Assessment of Export Potentials to Europe and Austria, **2019**, Research Reports, 11/2019, Austrian Foundation for Development Research (ÖFSE).
10. Ozguven, M.M., Adem, K., Automatic Detection and Classification of Leaf Spot Disease in Sugar Beet Using Deep Learning Algorithms, *Phys A: Stat Mech Appl*, **2019**, 535, 122537, <https://doi.org/10.1016/j.physa.2019.122537>.
11. Nithyaprakash, V., Niveathitha, S., Shanmugapriya, V., Designer Activism Strategies for Sustainable Leather Product Designs, in Muthu, S.S. (ed.), *Leather and Footwear Sustainability: Manufacturing, Supply Chain, and Product Level Issues*, **2020**, 57-89, [https://doi.org/10.1007/978-981-15-6296-9\\_4](https://doi.org/10.1007/978-981-15-6296-9_4).
12. Mirghani, M.E.S., Salleh, H.M., Che Man, Y.B., Jaswir, I., Rapid Authentication of Leather and Leather Products, *Advances in Natural and Applied Sciences*, **2012**, 6, 5, 651-660.

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# AUTOMATED EXTRACTION AND FUNCTIONAL CLASSIFICATION OF SOLE PATTERNS BASED ON DEEP LEARNING

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Received: 30.03.2026

Accepted: 25.06.2026

<https://doi.org/10.24264/lfj.26.2.5>

## AUTOMATED EXTRACTION AND FUNCTIONAL CLASSIFICATION OF SOLE PATTERNS BASED ON DEEP LEARNING

**ABSTRACT.** This study presented a computer vision-based method for the automatic extraction and functional classification of Outsole-Pattern design, which currently relies significantly on expertise and lacks digital support. An instance segmentation network based on the Mask-RCNN was utilised to segment the Outsole-Pattern from the image, thereby removing background interference during the pattern recognition. Subsequently, an existing deep-learning-based edge detector, DexiNed, was adopted to extract outsole-pattern edges, compute the greyscale map of the Outsole-Pattern lines. Finally, the EfficientNet served as the backbone network to classify the varied patterns according to their functional characteristics. Results demonstrated that the proposed framework effectively performed outsole's image segmentation and precise edge pattern extraction, five classes of functional pattern were categorized: the lateral, the longitudinal, the zigzag, the block-shaped, and the circular suction cups—based on foot functional areas. Furthermore, classification accuracy was generally over 90% on our custom datasets. This method establishes a structured pattern database that transforms design knowledge into reusable digital templates, enabling the transition in footwear design from experience-based to data-driven approaches, hence enhancing design efficiency and aligning with trends of industry digitalisation.

**KEYWORDS:** Outsole-Pattern, computer vision, edge detection, image segmentation, digital design of footwear

## EXTRAGEREA AUTOMATĂ ȘI CLASIFICAREA FUNCȚIONALĂ A MODELELOR DE TALPĂ EXTERIOARĂ PE BAZA ÎNVĂȚĂRII PROFUNDE

**REZUMAT.** Acest studiu a prezentat o metodă bazată pe viziunea computerizată pentru extragerea automată și clasificarea funcțională a modelelor de talpă exterioară, proces care, în prezent, se bazează în mare măsură pe expertiză și nu beneficiază de suport digital. S-a utilizat o rețea de segmentare de instanță pe baza Mask-RCNN pentru a segmenta modelul tălpii exterioare din imagine, eliminând astfel interferențele de fundal în timpul procesului de recunoaștere a modelelor. Ulterior, s-a utilizat un detector de margini existent, bazat pe învățare profundă, DexiNed, pentru a extrage marginile modelului tălpii exterioare și pentru a calcula harta în tonuri de gri a liniilor modelului tălpii exterioare. În final, rețeaua EfficientNet a servit drept rețea principală pentru clasificarea diverselor modele în funcție de caracteristicile lor funcționale. Rezultatele au demonstrat că acest cadru propus a realizat în mod eficient segmentarea imaginii tălpii exterioare și extragerea precisă a modelelor marginilor, fiind clasificate cinci categorii de modele funcționale: modelul lateral, cel longitudinal, cel în zigzag, cel în formă de bloc și cel cu ventuze circulare — pe baza zonelor funcționale ale piciorului. În plus, precizia clasificării a depășit, în general, 90% în seturile noastre de date personalizate. Această metodă creează o bază de date structurată a modelelor care transformă cunoștințele de proiectare în șabloane digitale reutilizabile, facilitând tranziția în proiectarea încălțămintei de la abordări bazate pe experiență la cele bazate pe date, sporind astfel eficiența proiectării și aliniindu-se la tendințele de digitalizare din industrie.

**CUVINTE CHEIE:** modelul tălpii exterioare, viziune computerizată, detectarea marginilor, segmentarea imaginilor, proiectarea digitală a încălțămintei

## EXTRACTION AUTOMATIQUE ET CLASSIFICATION FONCTIONNELLE DES MOTIFS DE SEMELLES EXTÉRIEURES À L'AIDE DE L'APPRENTISSAGE PROFOND

**RÉSUMÉ.** Cette étude présente une méthode basée sur la vision par ordinateur pour l'extraction automatique et la classification fonctionnelle des motifs de semelles extérieures, un domaine qui repose actuellement en grande partie sur l'expertise humaine et qui manque de support numérique. Un réseau de segmentation d'instances basé sur le Mask-RCNN a été utilisé pour segmenter le motif de semelle extérieure à partir de l'image, éliminant ainsi les interférences de l'arrière-plan lors de la reconnaissance des motifs. Par la suite, un détecteur de contours existant basé sur l'apprentissage profond, DexiNed, a été utilisé pour extraire les contours des motifs de la semelle extérieure et calculer la carte en niveaux de gris des lignes de ces motifs. Enfin, le réseau EfficientNet a servi de réseau central pour classer les différents motifs en fonction de leurs caractéristiques fonctionnelles. Les résultats ont démontré que le cadre proposé permettait de réaliser efficacement la segmentation des images de la semelle extérieure et l'extraction précise des contours des motifs, cinq classes de motifs fonctionnels ayant été identifiées : les ventouses latérales, longitudinales, en zigzag, en forme de bloc et circulaires — selon des zones fonctionnelles du pied. De plus, la précision de la classification dépasse généralement les 90 % sur nos ensembles de données personnalisés. Cette méthode permet

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de constituer une base de données structurée de motifs qui transforme les connaissances en matière de conception en modèles numériques réutilisables, facilitant ainsi la transition dans la conception de chaussures d'une approche fondée sur l'expérience vers une approche fondée sur les données, ce qui améliore l'efficacité de la conception et s'inscrit dans les tendances de la numérisation du secteur.

MOTS-CLÉS : motif de semelle extérieure, vision par ordinateur, détection des contours, segmentation d'images, conception numérique de chaussures

## INTRODUCTION

From a functional design perspective, outsoles' tread patterns that satisfy these functions can be categorized into the five functional categories defined in Section 1 (Fig. 1). They provide enhanced longitudinal flexibility and grip and are typically incorporated into footwear emphasizing flexibility (Fig. 1a). The longitudinal patterns (parallel to the direction of movement) offer superior longitudinal rigidity, smooth motion and lateral grip, and are suitable for shoes

requiring fluid rolling motion (Fig. 1b). The zigzag or hybrid patterns combine the advantages of both transverse and longitudinal designs, providing excellent slip resistance (Fig. 1c). The block patterns use protruding lugs to grip the ground, providing excellent traction, and are frequently used in racing shoes (Fig. 1d). The circular suction cup patterns are specifically designed for agile manoeuvring and are commonly found in basketball shoes and similar footwear (Fig. 1e). Collectively, these structural designs represent the tangible mechanisms through which the functional properties of the outsole are realized.

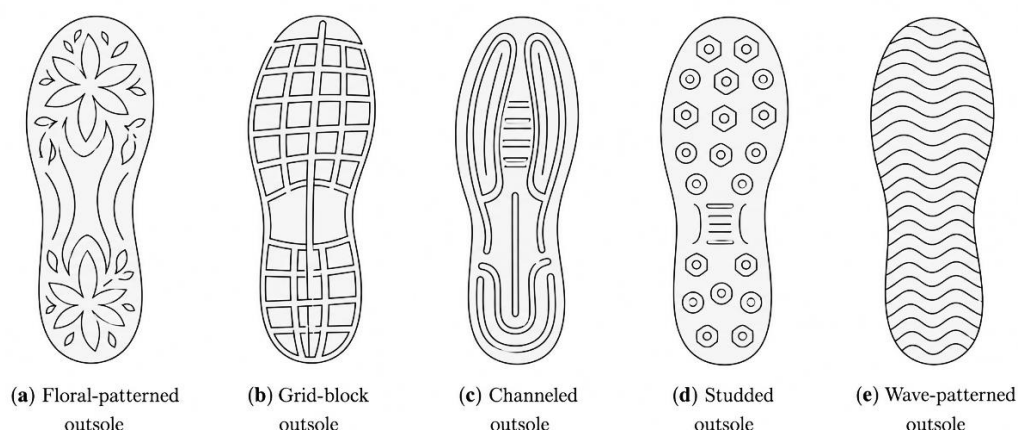


Figure 1. Representative examples of outsole pattern categories used for conceptual illustration

Recent research has recorded recognizing technologies related to footwear patterns. Richetelli *et al.* [1] exploited the Fourier transform method in criminal investigations, achieving an 88.5% accuracy rate in pattern classification for matching suspects' footprints; nevertheless, this technique has not been applied in footwear design. Traditional image recognition techniques are generally inadequate for supporting large-scale, independent design generation, necessitating the integration of advanced computer vision algorithms. The advent of Convolutional Neural Networks (CNNs) in image processing has facilitated their widespread adoption across classification and

detection tasks due to their high accuracy and generalizability. Mask Region-based Convolutional Neural Network (R-CNN), introduced by He *et al.* [2], enhances CNN designs by segmenting distinct areas, thus enabling the identification of contours for various categories. This technique has been extensively employed in domains such as facial identification, online virtual try-on, and virtual makeup applications.

Furthermore, instance segmentation and edge detection techniques in computer vision provided an efficient means of generating databases of shoe sole patterns with diverse functional characteristics. Conventional edge detection methods, such as

the Canny operator, can produce satisfactory results for greyscale images containing basic structural elements. However, deep learning-based approaches, particularly those employing CNN architectures, have demonstrated superior performance on benchmark datasets such as Berkeley Segmentation datasets 500 (BSDS500). The Dense Extreme Inception Network for Edge Detection (DexiNed), developed by Soria *et al.* [3], demonstrated exceptional edge detection proficiency and the ability to generate fine edges, making it particularly adept at recognizing complex patterns on shoes' outsoles.

Despite the structural simplicity of shoe outsoles' tread patterns, their myriad components, diminutive sizes, and irregular distribution render intelligent patterns notably difficult to recognize, necessitating the continual incorporation of new patterns into the database to maintain the currency of machine learning algorithms. The categorization of outsole patterns is not solely a visual differentiation, but a systematic classification grounded in their physical attributes and functional necessities for locomotion. Liu *et al.*'s edge detection technique [4] enabled the extraction of complex patterns, while Chituc [5] demonstrated enhanced design efficiency through structured databases in the digital transformation of the footwear industry. However, existing research has not performed thorough training on sole models, and the effectiveness of the resulting outsole pattern analysis requires improvement.

This work introduced a computer vision methodology for the automated extraction and functional categorization of patterns to address these challenges. Rather than proposing a new backbone network, the study organized established deep learning models into a task-oriented workflow for outsole-pattern analysis, providing a structured analytical framework for investigating the relationship between outsole-pattern morphology and functional performance.

## METHOD

### Datasets

This study utilized web crawler technologies to autonomously gather raw footwear photos from publicly accessible fashion platforms, including brand websites, e-commerce product pages, and runway image repositories, to create a representative training dataset. The crawler was developed using the Python-based Scrapy framework; it incorporated keyword filtering (e.g., 'trainers', 'high heels', 'boots') and anti-crawling measures to ensure data diversity and authenticity. Following deduplication, resolution filtering ( $\geq 512 \times 512$  pixels), and manual review, a final assemblage of 5850 high-quality footwear images was obtained, covering eight principal categories: sports, casual, formal, and outdoor footwear. A total of 2461 images with clearly identifiable outsole regions were utilized for outsole pattern analysis tasks. All data were exclusively intended for non-commercial academic research and had been anonymized to remove facial images and trademark details.

This study employed an internal footwear image dataset in conjunction with two notable public edge detection benchmark datasets—BIPED and BSDS500 for the evaluation and selection of edge detection methodologies. The BIPED dataset, presented by Soria *et al.* [3], consisted of approximately 25,000 high-resolution ( $1280 \times 720$ ) natural images. The annotations were independently performed by several observers, focusing on intricate edge structures discernible to the human eye, and were particularly suitable for texture-rich, detail-dense environments (such as textiles, masonry, and shoe outsole patterns). In contrast, BSDS500 was a traditional general-purpose benchmark for edge detection, developed by Arbeláez *et al.* [6], comprising 500 images of indoor and outdoor scenes. The annotations highlighted the primary outlines and semantic boundaries of objects, while generally overlooking micro-textural specifics.

## Design Framework for the Outsole-Pattern Analysis

Diverse gaits or postures exerted pressure on specific areas of the outsole during locomotion. This study delineated the outsole into three separate regions: the forefoot, midfoot, and heel (Figure 3). The technological process was organized as follows: the outsole pattern was first segmented to acquire the sole contour using the Mask-RCNN, followed by accurate pattern edge detection applying DexiNed. Evaluated using three standard metrics: Optimal Datasets Scale (ODS), Optimal Image Scale (OIS), and Average Precision (AP). The ODS measured the model's overall edge detection effectiveness across the datasets with a uniform threshold; the OIS evaluated the peak performance attainable with a separately selected optimal threshold for each image; while the AP assessed the model's sensitivity to subtle edges by examining the area under the precision-recall curve across multiple thresholds.

### Segmentation Algorithm

This study primarily used the Mask-RCNN technique, which was capable of simultaneously performing object detection, classification, and semantic segmentation tasks. The principal workflow of Mask-RCNN was outlined as follows: initially, a Residual Network (ResNet) functioned as the backbone network; through multi-scale feature extraction from the input image, features from

layers C1, C2, C3, C4, and C5 were obtained; these feature layers were utilized to construct a feature pyramid, enabling multi-scale fusion to generate effective feature layers. In the region extraction network, candidate bounding boxes of diverse proportions and sizes were generated according to the dimensions of the valid feature layers. Ultimately, redundant candidate boxes were eliminated through non-maximum suppression.

The ROI Pooling was performed on the valid feature layers of the selected candidate boxes to identify regions of interest, which were then fed into the object detection and semantic segmentation networks. In the object detection network, regression was performed for localization, followed by non-maximum suppression to obtain the final predicted bounding box, while simultaneously detecting and classifying objects within the candidate boxes. The resulting bounding box was fed into the semantic segmentation network, which employed it to extract the pertinent feature layer and segment its pixels. This process ultimately generated extensive semantic segmentation data.

### Pattern Detection Algorithm

DexiNed was adopted in this study as a pre-trained edge-detection model for extracting outsole-pattern edges. Since the purpose of this work was not to redesign the edge detector itself, detailed architectural settings are referred to in the original publication.

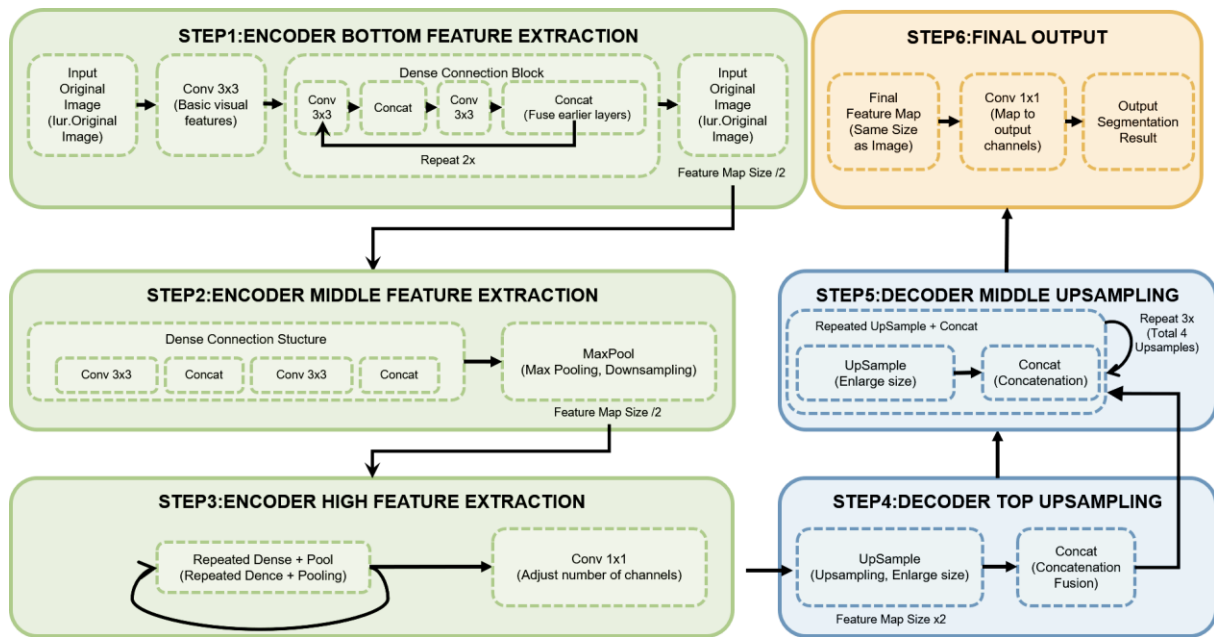


Figure 2. The DexiNet network architecture

The DexiNet network consisted of two main components: the Dexi network and the upsampling module (shown by the blue portion). Upon inputting an RGB image into the Dexi network, feature extraction occurred (Dexi excelled at preserving edge information); the resultant feature maps were further processed by the upsampling module to create edge images, which were ultimately combined to yield the final edge image.

The green block had two stacked convolutional layers, each featuring a kernel size of 3×3, followed by batch normalization, and employed ReLU as the activation function (in the final sub-block, only the last convolutional kernel was active). The max-pooling layer was set with a 3×3 kernel and a stride of 2. The design employed a multi-scale learning approach akin to HED, followed by an upsampling procedure. Due to the potential loss of significant edge features in deeper convolutional layers (as demonstrated in DeepEdge), from the third block onwards, the outputs of the sub-blocks employed edge-connected averaging (indicated by the green parts).

The upsampling module was composed of conditionally stacked sub-blocks, each containing a convolutional layer and a

deconvolutional layer. Two categories of sub-blocks existed: Sub-block 1 was activated by either Dexi or Sub-block 2 and was utilized exclusively when the scale disparity between the feature map and the reference standard was exactly 2; Sub-block 2 was employed only when the scale disparity exceeded 2 and was applied iteratively until the scale disparity was reduced to 2. Sub-block 1 consisted of a 1×1 convolution, followed by a ReLU activation function, and culminated in a deconvolution of size S×S, with S representing the dimensions of the input feature map. The final convolutional layer was devoid of an activation function. Sub-block 2 was configured identically to Sub-block 1, with the only difference being the number of filters. The upsampling process in the second layer of the sub-block could be performed with bilinear interpolation, subpixel convolution, or transposed convolution.

DexiNet could be articulated as a regression function, as delineated in Equation 1, where X represented the input image and Y was the corresponding reference standard.

$$Y' = \delta(X, Y) \quad (1.)$$

The loss function was articulated by Equation 2:

$$L = -(1 - \beta) \sum_{j \in Y} \log \sigma(y_j = 0 | X; W, W^n) \quad (2.)$$

In this context,  $W$  signified the collection of all network parameters, comprising  $n$  associated parameters, whereas  $\delta$  specified the weight assigned to each scale level.  $\beta = Y/(Y + X)$ ,  $1 - \beta = (Y + X)/Y$ , where  $X$  and  $Y$  represented the edges and non-edges in the reference standard, respectively. We intended to analyse the three parameters—ODS, OIS, and AP—in accordance with the technique.

To assess the efficacy of this approach, we integrated RCF [4] and PidiNet [7] while examining the individual patterns in the BIPED datasets (<https://github.com/xavyasp/BIPED>) and the BSDS500 datasets (<https://www2.eecs.berkeley.edu/Research/Projects/CS/vision/grouping/resources.html>). The selection of these two datasets was predicated on their complementary annotation attributes: BIPED emphasised fine edges discernible to the human eye in high-resolution images (including textures, fabrics, and microstructures), rendering it appropriate for assessing a model's capacity to replicate intricate details in shoe soles; conversely, BSDS500 focused on object contours and semantic boundaries, highlighting overall structural integrity, and was frequently employed for benchmarking general-purpose edge detection algorithms. By juxtaposing results from these two datasets, we were able to thoroughly assess how various approaches

reconciled detail fidelity with contour coherence.

### Design Framework for the EfficientNet

For information concerning EfficientNet architecture, reference was made to the study by Mingxing Tan *et al.* [8]. Classification of footwear was conducted according to silhouette style: skate shoes—low-top, mid-top, and high-top; trainers—running shoes, football boots, and trail shoes; boots—high-top and low-top.

Presently, three assessment measures were commonly utilised for edge detection: fixed contour threshold (ODS), per-image best threshold (OIS), and average precision (AP). This work utilised the F-measure of AP, ODS, and OIS to evaluate the efficacy of several prominent edge detectors from recent years, with  $F$  defined by Equation 3.

$$F = \frac{2 \times \text{precision} \times \text{recall}}{\text{precision} + \text{recall}} \quad (3.)$$

Figure 3 illustrates the processing workflow used for outsole-pattern analysis in this study. The original footwear image was first processed by Mask R-CNN to segment the outsole region; subsequently, pre-trained DexiNed was employed to extract outsole-pattern edges; finally, EfficientNet was used to classify the extracted pattern representation into functional categories.

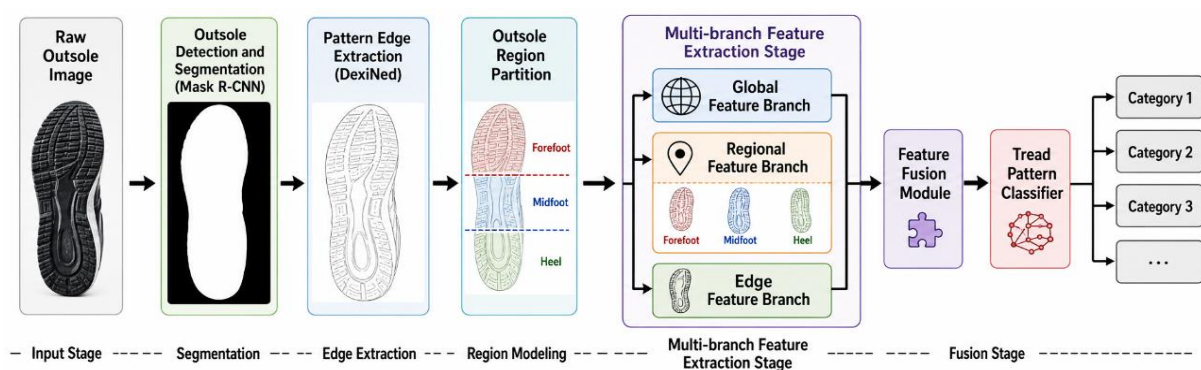


Figure 3. Framework for Outsole Pattern Detection



## RESULTS

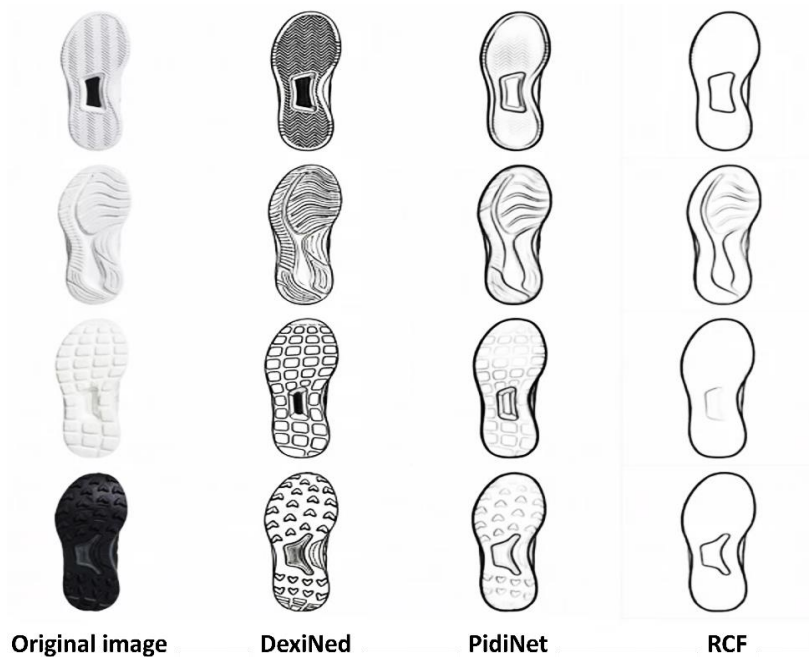


Figure 4. Results of Outsole Segmentation and Edge Detection

Figure 4 illustrated the effectiveness of edge detection for the three algorithms—the DexiNed, PidiNet, and RCF—on individual patterns. From a visual and qualitative standpoint, only the DexiNed was able to accurately reconstruct the fine textural details of the shoe sole. In contrast, the PidiNet and the RCF, due to their multi-pooling network architectures, failed to capture a significant portion of the subtle textures during feature propagation. Consequently, their output edges appeared blurred and coarse, making them unsuitable for the development of a high-precision shoe outsole pattern database.

This phenomenon could be attributed to the underlying principles of algorithmic design. The DexiNed, introduced by Soria *et al.* [3] and motivated by HED and Xception networks, generated visually distinct thin edge maps through dense extreme initial modules, thereby obviating the need for task-specific fine-tuning. It demonstrated superior ODS/OIS performance on benchmark datasets such as BIPED and excelled in tasks requiring precise structural reconstruction, including the extraction of micro-patterns from shoe soles. PidiNet, developed by Su *et al.* [7], aimed to integrate conventional edge operators (e.g.,

the Canny and the Sobel) into convolutional processes to facilitate backbone edge extraction (ODS = 0.807 on BSDS500 at 100 FPS); however, its lightweight architecture prioritized contour continuity and inference efficiency, resulting in compromised micro-texture fidelity. In contrast, RCF [4] employed the hierarchical pooling mechanisms characteristic of deep networks such as VGG, which inevitably caused the loss of fine-grained spatial information during deep feature abstraction. Therefore, within the context of developing a high-fidelity, single-database framework for functional categorization in this study, DexiNed's ability to preserve delicate edge structures rendered it the most suitable choice.

To further evaluate the efficacy of DexiNed, we performed a quantitative study on the BSDS500 and BIPED datasets. Table 1 illustrated that on the BIPED datasets, which closely mimicked the intricate texture of shoe soles, the DexiNed attained ODS, OIS, and AP scores of 0.859, 0.867, and 0.905, respectively. These scores markedly surpassed those of SED, HED, and the recently high-performing edge detection network RCF (ODS: 0.843; OIS: 0.859; AP: 0.882), thereby affirming its dominance in

fine-grained edge detection at the data level. On the general-purpose natural scene dataset BSDS500, DexiNed's scores (ODS: 0.729; OIS: 0.745; AP: 0.689) were markedly inferior to those of RCF (ODS: 0.811; OIS: 0.830; AP: 0.846) and PidiNet (ODS: 0.807; OIS: 0.823; AP:

0.834). This mismatch arose because BSDS500 was not explicitly intended for edge detection tasks; its evaluation metrics penalized the delicate edges identified by DexiNed, which were essential traits to preserve for creating a high-precision solitary pattern database.

Table 1: Performance Comparison of Edge Detection Models

| Datasets | Model   | ODS   | OIS   | AP    |
|----------|---------|-------|-------|-------|
| BIPED    | SED     | 0.717 | 0.731 | 0.756 |
| BIPED    | HED     | 0.829 | 0.847 | 0.869 |
| BIPED    | RCF     | 0.843 | 0.859 | 0.882 |
| BIPED    | DexiNed | 0.859 | 0.867 | 0.905 |
| BSDS500  | SED     | 0.71  | 0.74  | 0.74  |
| BSDS500  | HED     | 0.79  | 0.808 | 0.811 |
| BSDS500  | RCF     | 0.811 | 0.83  | 0.846 |
| BSDS500  | PidiNet | 0.807 | 0.823 | 0.834 |
| BSDS500  | DexiNed | 0.729 | 0.745 | 0.689 |

To assess the algorithm’s precision, our datasets with 2461 available outsole figures were assessed. Following instance segmentation and edge detection, the images were partitioned into forefoot, midfoot, and heel regions and subsequently input into the EfficientNet network for classification; the results were presented in Figure 5. Circular suction cups were exclusively located in the forefoot region, resulting in the absence of corresponding classification data for the remaining regions. This pattern achieved the highest classification accuracy (0.98) within the forefoot region, attributable to its distinctive morphological characteristics. In contrast, the zigzag pattern, characterized by ambiguous

textural features and a propensity for confusion with horizontal or vertical patterns, exhibited reduced overall classification performance, with the lowest accuracy observed in the midfoot region (0.82), followed by the forefoot (0.89) and heel (0.88). Block patterns demonstrated consistently high classification accuracy across all foot regions, with rates exceeding 0.90 (0.91 for the forefoot, 0.95 for the midfoot, and 0.91 for the heel). The classification accuracies of horizontal and vertical patterns were comparable across regions, consistently ranging from 0.89 to 0.91 with minimal variation, reflecting uniform performance.

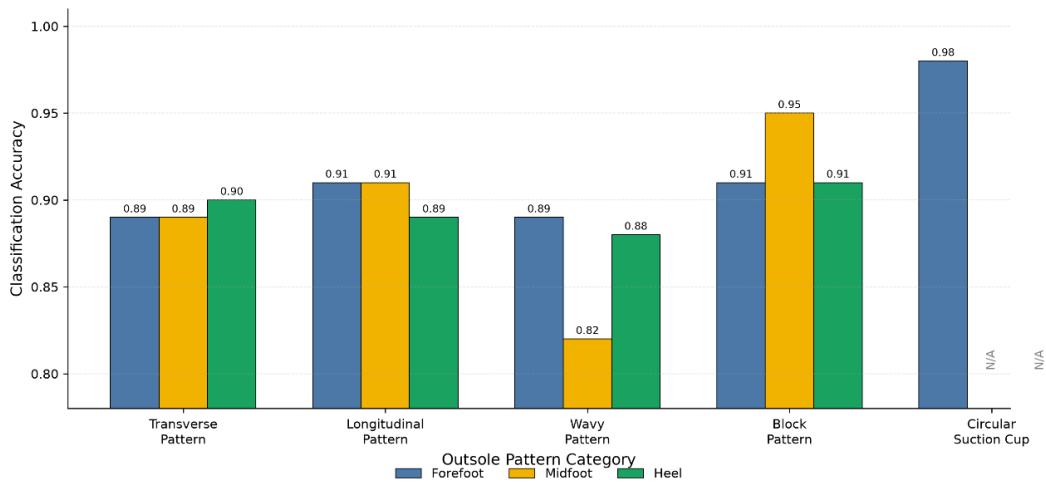


Figure 5. Comparative Analysis of Pattern Classification Accuracy Across Various Foot Regions

## DISCUSSION

The present study should be understood as an application-oriented and task-specific methodological framework rather than an attempt to propose new backbone architecture for edge detection or segmentation. The main contribution does not lie in redesigning DexiNed, Mask R-CNN, or EfficientNet at the network level, but in organizing these established models into a coherent pipeline for outsole-pattern analysis. In particular, the methodological value of this work is reflected in three aspects: (1) the construction of a complete workflow linking sole segmentation, pattern-edge extraction, and function-oriented classification; (2) the introduction of outsole region partitioning into forefoot, midfoot, and heel to better align visual pattern analysis with functional interpretation; and (3) the task-specific adaptation of model selection, preprocessing, and category definition for the outsole-design scenario.

From this perspective, the contribution of the study is a form of workflow-level and domain-oriented innovation. Although the underlying backbone models are established methods, their direct use does not automatically yield a usable analytical framework for outsole-pattern design. The outsole domain presents distinctive challenges, including dense micro-textures, irregular local structures, and functionally meaningful regional variation. Therefore, integrating existing models into a structured and interpretable pipeline is itself a meaningful step toward digital design support in footwear research.

At the same time, this study has several limitations. It does not propose a newly designed edge-detection architecture, nor does it investigate architecture-level optimization specifically for outsole data. Future work may focus on building a larger outsole-specific benchmark, improving region-aware feature modeling, and developing more specialized edge-extraction and classification strategies for fine-grained outsole-pattern analysis.

## CONCLUSION

This study presented and validated a comprehensive computer vision-based framework for the automated analysis and functional classification of shoe sole patterns. The proposed method first employed the Mask R-CNN model to segment the sole region from raw images. The framework integrates established deep learning models for sole segmentation, pattern-edge extraction, and downstream classification into a unified workflow tailored to outsole-pattern analysis. Results demonstrated that the framework achieved high identification accuracy and robust performance, even in complex image backgrounds. The above findings highlight the potential of transforming traditional, experience-based design methods into data-driven intelligent design approaches, which can improve design efficiency and align with contemporary trends of digitalization and rapid iteration in the footwear manufacturing industry.

## REFERENCES

1. Richetelli, N., Lee, M.C., Lasky, C.A., Gump, M.E., Speir, J.A., Classification of Footwear Outsole Patterns Using Fourier Transform and Local Interest Points, *Forensic Sci Int*, **2017**, 275, 102-109, Epub 2017 Mar 4, PMID: 28343023, <https://doi.org/10.1016/j.forsciint.2017.02.030>.
2. He, K., Gkioxari, G., Dollar, P., Girshick, R., Mask R-CNN, *IEEE Trans Pattern Anal Mach Intell*, **2020**, 42, 2, 386-397, Epub 2018 Jun 5, PMID: 29994331, <https://doi.org/10.1109/TPAMI.2018.2844175>.
3. Soria, X., Riba, E., Sappa, A., Dense Extreme Inception Network: Towards a Robust CNN Model for Edge Detection, 2020 IEEE Winter Conference on Applications of Computer Vision (WACV), Snowmass, CO, USA, **2020**, pp. 1912-1921, <https://doi.org/10.1109/WACV45572.2020.9093290>.
4. Liu, Y., Cheng, M.M., Hu, X., Bian, J.W., Zhang, L., Bai, X., Tang, J., Richer Convolutional Features for Edge Detection, *IEEE Trans Pattern Anal Mach Intell*, **2019**, 41, 8, 1939-1946, <https://doi.org/10.1109/TPAMI.2018.2878849>.
5. Chituc, C.M., Interoperability in the Footwear Manufacturing Networks and Enablers for Digital Transformation, in: Cherfi, S., Perini, A., Nurcan, S. (eds.), *Research Challenges in Information*

- Science. RCIS 2021. Lecture Notes in Business Information Processing*, vol 415, Springer Cham, **2021**, [https://doi.org/10.1007/978-3-030-75018-3\\_39](https://doi.org/10.1007/978-3-030-75018-3_39).
6. Arbeláez, P., Maire, M., Fowlkes, C., Malik, J., Contour Detection and Hierarchical Image Segmentation, *IEEE Trans Pattern Anal Mach Intell*, **2011**, 33, 5, 898-916, <https://doi.org/10.1109/TPAMI.2010.161>.
  7. Su, Z., Liu, W., Yu, Z., Hu, D., Liao, Q., Tian, Q., Pietikäinen, M., Liu, L., Pixel Difference Networks for Efficient Edge Detection, 2021 IEEE/CVF International Conference on Computer Vision (ICCV), Montreal, QC, Canada, **2021**, pp. 5097-5107, <https://doi.org/10.1109/ICCV48922.2021.00507>.
  8. Tan, M., Le, Q., Efficientnet: Rethinking Model Scaling for Convolutional Neural Networks, Proceedings of the 36<sup>th</sup> International Conference on Machine Learning, Long Beach, California, PMLR 97, **2019**, 6105-6114.

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## EUROPEAN RESEARCH AREA

### COTANCE NEWSLETTERS

Starting with January 2019, the COTANCE Council has issued a monthly **COTANCE Newsletter** with the purpose of **promoting an improved image of leather** to relevant decision makers and domestic stakeholders including Members of the European and National Parliament, Governmental authorities, Ministerial officers, Customers of the leather industry, Brands, Retail chains, Relevant NGOs, Designers, etc. The monthly newsletters present topics that tell the truth about a controversial aspect or a fact that is not well known by the general public to bring about a better understanding of leather and the European leather industry, as well as a positive predisposition to legislate in favor of the leather industry. The newsletters are available in seven languages at <https://www.euroleather.com/leather/newsletter>, and were also published in the 2019-2025 issues of *Leather and Footwear Journal*.



NEWS 2/2026



### ***Women in Tanneries: Special Women's 3rd Edition***

March is our moment to celebrate women — their talent, ambition and the impact they make every day. After the success of our 2024 and 2025 editions, spotlighting women in the leather industry has become a proud COTANCE tradition.

This year, we take you closer to the reality of the sector through the story of inspiring professionals from Sweden & Italy. Through their daily experience, they reveal what working in leather truly looks like: dynamic, demanding, creative and deeply rewarding. From the factory floor to leadership, their journey shows how the industry offers space to grow, lead and balance professional and personal life.

Their stories are a powerful reminder that the leather sector is continuously evolving — and opening new opportunities for those ready to shape its future.



## Meet our Stars

“My name is Ulrika Andersson, and I am the CEO of [Tärnsjö](#) Tannery. I am married and the mother of a 16-year-old daughter. As I approach my third year at Tärnsjö, I continue to feel the same sense of purpose I felt the first time I stepped into the tannery, a place where craftsmanship, tradition, and responsibility meet.”



“I am Barbara Boschetti, CEO of [Conceria Laba](#), a company founded by my father. I am a mother of three and have worked in the company for about thirty years, a journey that has allowed me to grow professionally alongside the family business.”

## What does a typical work day look like for you - from the moment you arrive to the moment you leave?

UA: I start the day by walking around the factory and greeting all employees. Some days the tour takes 15 minutes, other days 40–45 minutes. It's nice and important to chat with the employees. My days are filled with a mix of meetings, production challenges, strategic projects, staff matters, and customers visiting the factory.

BB: My day starts early: I drop my son off at school and arrive at the company around 8:00 AM. The first thing I do is walk through the various departments of the tannery; it is a fundamental moment to check in with the managers and get a feel for the production situation. Production is the heart of the company, and that is where I dedicate most of my time. During the day, I also handle reading reports to monitor progress and make informed decisions. On a weekly basis, I set aside time for meetings, both operational and strategic. I return home around 6:30 PM.

## What is the part of the day you enjoy the most?

UA: When I see all the beautiful leather and items, we deliver every day. I'm so proud of our loyal and dedicated employees who have produced such excellent craftsmanship with premium quality.

BB: The moment I prefer is the morning. It is the most dynamic phase of the day, when energy, decisions, and new challenges are concentrated. It is the moment when the day's work is truly built.

## How does your job allow you to balance professional life with personal interests, family or hobbies?

BB: It wasn't easy, especially when my children were little. In those years, I relied on a lot of help and had to make choices, often putting my personal interests on the back burner. For a long

time, I split my energy between work and family. Today, with older children, I can carve out more space for myself while continuing to dedicate myself to work with passion.

UA: My job is very demanding, but it allows me to maintain a balance between work, family, and hobbies. When I'm at the factory, I focus fully on work, which allows me to have more free time at home. While my role remains a central part of my life, I carve out time for my private life. Outside of work, my job inspires me to look out for beauty and nature; I have a deep appreciation for craftsmanship in all its forms. I like sports and skiing is my way of recharging in nature. My days often end with a walk alongside our dog Bowie.



[Conceria Laba, Italy](#)

### **What motivates you to grow in this industry? What are your ambitions for the future?**

UA: Our unique vegetable tanned leather that has a beautiful look and only gets more beauty with age. Our ambition is to grow the business and generate more resources through increased sales over the years for continued investments in the factory.

BB: What motivates me most is the possibility of operating in a sector where learning is a continuous progress. Leather, as a natural material, possesses unique and variable characteristics that make every production process stimulating and never repetitive. My ambition is to continue the company's growth path, facing market evolutions with a structured approach oriented towards quality, innovation, and sustainability. In this context, I believe it is fundamental to help reaffirm the value of leather as a natural, noble, and durable material, distinguished by high resistance, longevity, and uniqueness. It is a material that, if correctly processed and used, maintains and increases its characteristics over time, serving as a concrete alternative to unsustainable consumption models. The goal is to promote greater awareness, both in the market and among final consumers, regarding the intrinsic value of leather and its role within a responsible supply chain.

### **Why is this an exciting time for women to join the leather industry?**

BB: Today is a particularly interesting time because the sector is changing and there is increasing attention to innovation, sustainability, and managerial skills. Women can bring an important contribution in terms of sensitivity, organization, and vision. More and more companies are valuing female talent, including in leadership roles. It is a sector that offers concrete opportunities for growth and where women can truly make a difference.

UA: It's one of the world's oldest industries, traditionally dominated by men working in the tannery. The work is physically demanding and requires both strength and endurance. Today, we have three women on the tannery floor, and they genuinely enjoy the physical aspect of the job. A

powerful shift is underway, a widening of space where women's strength, leadership, and perspectives are not only welcome but essential. The industry is evolving, and women are actively shaping that evolution in real time.



[Tärnsjö Garveri, Sweden](#)

Ulrika's and Barbara's stories reflect a broader transformation taking place across the leather industry.

Today, women are not only part of the sector — they are leading it, shaping it and redefining it. Their perspectives, skills, and leadership are essential to building a more inclusive, resilient, and forward-looking industry.

At COTANCE, we believe that showcasing these real experiences is key to inspiring the next generation. The leather industry offers meaningful careers, combining tradition, innovation and purpose — and it is ready to welcome more talent.

**The future of leather is not only sustainable and innovative — It is also human, diverse and full of opportunity.**

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[UNIC - Concerie Italiane](#)

## COTANCE Newsletter April-May 2026



NEWS 3/2026

### *The Art of Making Leather: What Chemistry Really Tells Us*

Ask what tanning does and some people will say: it stabilises collagen, makes the hide heat-resistant & protects it against microbiological attack. That is largely correct, but it is also incomplete — and the gap between that partial answer and the full picture has real consequences for how our industry communicates, innovates, and competes.

#### **What Tanning Actually Means**

Under typical use conditions leather is a stable material - not only mechanically but against microbiological attack as well. The reason is straightforward: bacteria and fungi need moisture to grow or even survive, and dry leather, with a residual moisture content of 10 to 15%, simply does not provide it. A short period with water present — like a walk in the rain — is not enough to trigger measurable microbiological damage, but prolonged wet storage without preservation is another story.

So why not simply dry the hide? Because drying alone does not produce leather — it produces parchment (see picture below). A raw, delimed hide is essentially collagen dispersed in water. Remove the water without treatment and the collagen fibers collapse, bonding ionically to each other and producing parchment — stable against microbial attack, but useful only for very specific applications and extremely difficult to reprocess.



On the photo: parchment from bovine split. A rigid material because fibers are “glued” together after drying.  
Photo courtesy of [Filk Freiberg Institute gGmbH](#), 2026



Something is needed that replaces the water as the agent that keeps collagen flexible and fixes itself to an extent not to evaporate or migrate out under normal use conditions.

### Leather Making Techniques

One of the oldest tanning procedures does exactly that: Chamois tanning - one of the most ancient tanning techniques still in use. Rather than crosslinking the collagen, it works by covalently bonding hydrocarbon chains into the spaces between fibers — replacing the water molecules and keeping the fibers apart. The result is surprising: chamois leather actually has a lower heat resistance than untreated hide. Yet it is the only leather in the world that can be washed repeatedly with cold water and still recover its properties after drying.

In the picture below you can see the excellent fiber separation, with some long and thin fibers sticking out of the material, that results in a very soft article.



*On the photo: chamois tanning leather: the grain has been removed, the remaining reticular layer of the hide shows excellent fiber separation which results in a very soft and plyable article. Long, thin fibers sticking out of the material. Photo courtesy of [Filk Freiberg gGmbH](#), 2026*

Unfortunately, like for parchment, chamois leather is best for one article only, a very soft one. But it represents the second, maybe more important action of a tannage:

### Fiber Separation

Most other tanning agents work by bonding to multiple points in the collagen — stabilizing it and making it heat resistant. Without that, industrial-scale production would not be possible. The heat generated by faster processing and high-speed machinery would damage the intermediate before it ever became leather. Once dry, however, the temperature resistance of all tannages is sufficient for normal use, and behavior to heat treatment is different to what would be expected from the shrinkage temperature comparison alone.

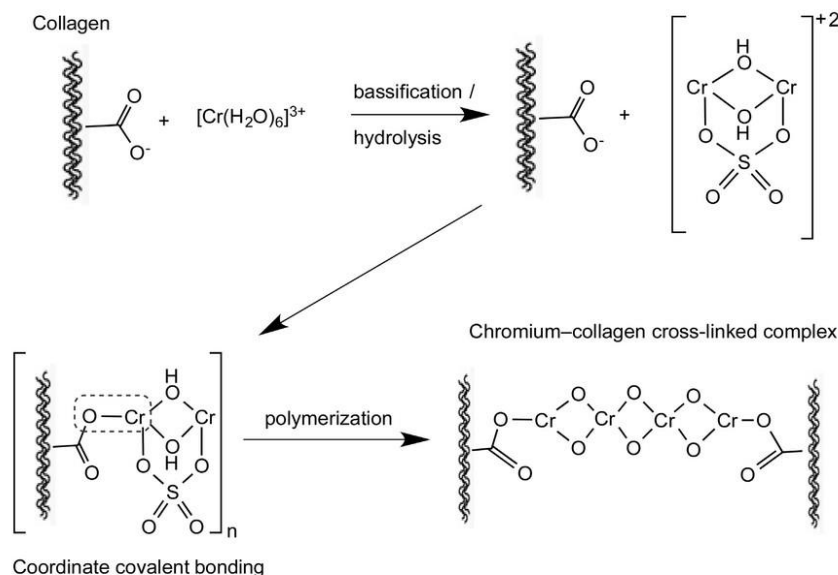
#### Different tannins use different chemical mechanisms

- Reactive tannins like glutaraldehyde do interact with the amino-functions of the collagen to form covalent bonds. Individually most stable, but low in number.
- Mineral tannins like chrome(III) do interact with the carboxylic functions of the collagen to form ionic/complex bonds. A good compromise of individual stability and number.
- Vegetable and Synthetic tannins do interact with both to form polar hydrogen-bridges. Big in numbers, but individually weak.

Some alternatives — zeolites, polymethacrylic acid, enzymatic crosslinking — can raise heat resistance, but each comes with a significant trade-off: a narrow working range, or reduced space for the fibre separation that good leather requires. They solve one problem while creating another.



Chromium(III), preferably offered as Sulfate, is and will remain the tannin with the best individual performance. Of every mineral scientifically tested, including uranium, nothing fits the collagen structure as well. It stabilises, separates fibers, and produces a leather that stays flexible when dry and can even be re-wetted. As a practical bonus, chrome-tanned leather shrinks predictably under dry heat and holds its shape afterwards — which is precisely why it remains the material of choice for shoe construction.



One thing all tannins have in common: none achieves sufficient fiber separation on its own for most leather articles. That is why fatliquoring — the introduction of hydrocarbon chains into the leather during crusting — remains an essential step. Think of it as Chamois tanning but not fixed in a way strong enough for laundering.

### Takeaways and What Does This Mean for the Future

Making leather is the art of combining tanning agents to achieve two things at once: stabilising the collagen so it resists heat and decay, and separating the fibers so the leather stays flexible once dry. Everything else in the process serves one or both of those objectives.



On the photo: bovine, full grain crust with its more dense, horizontal fiber structure on the grain side, and the more open, longer and vertical fibers towards the flesh side. Photo courtesy of [Filk Freiberg Institute gGmbH](#), 2026

Collagen structure is not going to change. The interaction sites available to tanning agents remain fixed by biology — which means the chemistry operates within boundaries that are unlikely to shift anytime soon. Those boundaries have been thoroughly tested. The tanning agents used today are not the only ones that have ever been tried — they are the ones that survived scrutiny.

Stop looking for miracles. Work with the best available chemistry and technologies. Build the strongest processes and controls around them. Invest seriously in competence and training — because most quality failures in leather production today are not chemistry problems. They are human ones: insufficient knowledge, inadequate process control, avoidable mistakes.

And finally: build on what leather does better than anything else. Durability. Natural performance. Versatility. Do not try to compete with plastics on their terms. That is not leather's court — and it does not need to be.

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Skins Pictures Courtesy of [Filk Freiberg Institute GmbH](#), 2026

## IULTCS NEWSLETTER

*Edition 13, 2025***Welcome**

This is the thirteenth edition of our scientific newsletter, bringing you the latest developments in research, regulations, technology, and standardized methods in the leather industry.

*NOTE: This newsletter is in English, Spanish, Portuguese and Turkish. One version after the other.* [LFJ Editor's note: For other language versions please visit [www.iultcs.org](http://www.iultcs.org)].

In this issue, we feature an interview with Mr. Eric Poles, Business Unit Leather Sales Director of Silvateam, located in Mondovì, Cuneo Province, Italy.

IULTCS appreciates working with Mr. Poles, member of the Italian Leather Association AICC, that has dedicated his entire career to the leather industry and has made several contributions through congress presentations and publications in Italy and abroad.

We appreciate Mr. Poles' collaboration with IULTCS Newsleather.

Please share your comments and suggestions to [secretary@iultcs.org](mailto:secretary@iultcs.org)

Subscribe to the Newsleather here: <https://bit.ly/3NsXNeL>

Kind regards,  
Dr. Luis A. Zugno, editor

**IULTCS INTERVIEW****Lifeline: Mr. Eric Poles****BU Leather Sales Director of Silvateam, Mondovì, Cuneo province, Italy**

Graduated in Leather Technology from the National Leathersellers' Centre in Northampton (1984), Eric has built an internationally recognised reputation in the field of vegetable extracts and leather chemicals.

He joined Silvateam in 1984 and has held progressively senior roles within the company: Technical Specialist (1984–1990), Technical Director (1990–2008) and currently Global Sales Director (2008–present).

With over 40 years of experience in leather tanning technologies, he has developed deep expertise in vegetable tanning and chrome-free leather processing, combining strong technical knowledge with strategic commercial leadership.

*IULTCS Question 1: Mr. Eric, please tell us a brief history of the Silvateam and the current status of your company (locations, number of employees, labs, etc.)*

Silvateam has been recognised as a global leader in tannin production since 1854. For more than 170 years, it has specialised in extracting and enhancing high-value plantbased molecules, developing high-performance solutions rooted in the biochemistry of natural polyphenols. Website: <https://www.silvateam.com/en/>

The company is firmly committed to supporting the transition from synthetic, fossilbased chemistry to renewable, bio-based alternatives. This strategic direction reflects a long-standing dedication to environmental responsibility and to restoring balance between industrial development and natural ecosystems.

This family-owned enterprise generates an estimated annual turnover of €200 million in 2025 and employs more than 800 people worldwide. Today, the company operates:

- 5 production sites
- 10 Development & Application Centres
- A commercial presence in over 60 countries

Beyond the leather business, Silvateam's expertise extends to food and beverage, nutraceuticals, cosmetics, oenology, brewing, agriculture and other industrial applications. In 2025, approximately €11 million was invested in research and development, reinforcing the company's focus on innovation, carbon footprint reduction, circular economy models and the valorisation of renewable raw materials. Within the leather industry, Silvateam offers a comprehensive portfolio designed to ensure both process efficiency and sustainability throughout the entire leather tanning cycle. Core products include natural tannins derived from chestnut, quebracho, tara, gallnuts and other botanical sources. These are complemented by syntans, specialty extracts, oils and fatliquors, tanning auxiliaries, resins, anionic dyes and beamhouse chemicals for the wet end. Through a strategic partnership with Biofin, Silvateam also provides finishing solutions.

Innovation, quality and technical problem-solving remain central to the company's approach. The development of sustainable leather technologies is a key pillar of its longterm strategy, including:

- High performing vegetable tanning technologies
- Chrome-free and metal-free solutions
- Low- and zero-bisphenol retanning systems
- High bio-based content formulations
- Eco-design of chemicals and processes
- Reduction of carbon footprint and wastewater impact

Over the past decade, Silvateam has further strengthened its expertise in the automotive sector, delivering tailor-made sustainable systems that meet the increasingly stringent technical and environmental standards required by global OEMs.

Since its foundation, environmental stewardship has been an integral part of Silvateam's identity. Sustainable forest management, efficient energy use, and optimised raw material valorisation continue to guide the company's operations and its future development strategy.



Figure 1: Silvateam plant in Corsaglia di Frabosa (Piedmont, Italy), 1854



Figure 2: Today's Silvateam headquarters in San Michele Mondovì (Piedmont, Italy)

*IULTCS Question 2: Silvateam is the world leader in the production of tannins for leather production. Please give us an overview of the current status of quebracho, tara, chestnut, olive pruning and gallnut production.*

Silvateam produces approximately 25,000 tons of vegetable extracts annually for the leather industry, based on a diversified and geographically balanced raw material sourcing strategy.

The extraction of vegetable tannins has historically been carried out using hot water only, without chemical solvents or reagents. This long-established process highlights the inherently sustainable nature of vegetable tannins as renewable bio-based resources — a characteristic that aligns well with evolving environmental expectations and has always been part of their industrial DNA.

The current production structure can be broadly described as follows:

- Quebracho: ~45–50%
- Chestnut: ~30–35%
- Tara: ~10–15%
- Olive-based extracts: growing share (currently <5%, but rapidly expanding)
- Gallnuts and specialty extracts: niche volumes (<5%)

Around 70% of Silvateam leather turnover is based on natural, sustainable, biobased products.

### **Chestnut**

Chestnut remains the historical backbone of Silvateam's vegetable tannin production. Approximately 80% of the chestnut wood (*Castanea sativa*) is sourced within a 70 km radius of the headquarters site in San Michele Mondovì (Italy), ensuring a short, traceable and low-impact supply chain.

Local chestnut forests continue to flourish thanks to traditional *coppicing* practices, a regenerative forestry management technique in which trees are cut at the trunk level while the root system remains intact. From the same stump, multiple new shoots naturally regrow, allowing the forest to renew itself without the need for replanting. This method preserves soil stability, promotes biodiversity and guarantees continuous biomass production over successive harvesting cycles.



Part of the supplying forests are managed under PEFC (Programme for the Endorsement of Forest Certification), ensuring compliance with strict environmental and traceability standards.

Chestnut tannins are widely used in traditional vegetable tanning as well as in modern metal-free and hybrid retanning systems, appreciated for their balanced reactivity, fullness and warm tone.

### **Quebracho**

Quebracho tannins are extracted from the heartwood of *Schinopsis balansae* species native to the Gran Chaco region in Argentina. Silvateam operates a long-established industrial extraction facility in La Escondida (Argentina), where quebracho wood is processed into high-performance tannin extracts.

Most of the raw material is sourced within a 300 km radius of the extraction plant through responsible selective thinning practices, supporting sustainable forest management and local economic development.

Quebracho extracts are characterised by high reactivity and structural firmness, making them particularly suitable for heavy leathers, vachetta-style articles and structured retanning systems.

### **Tara**

Tara is primarily produced in Peru, where Silvateam operates three plantations and a processing facility in Chilca. The production from owned plantations is complemented by structured sourcing from local farming communities under multi-year agreements that ensure stable supply, fair pricing, and social responsibility.

Tara (*Caesalpinia spinosa*) thrives in desert areas as well as high-altitude microclimatic conditions typical of Peru, which explain why large-scale cultivation has not been successfully replicated elsewhere.

From a technical perspective, tara provides high-purity hydrolysable tannins characterised by very light colour, excellent light and heat fastness, and high uniformity. These properties make tara particularly suitable for automotive, upholstery, and specialty leathers where brightness, colour consistency, and performance stability are critical.

### **Olive Pruning Extract (Olivenleder® / wet-green®)**

Olive-based extracts are derived from Mediterranean olive tree pruning residues, transforming agricultural by-products into high-performance tanning agents. Although currently representing a smaller share of total volume, olive extracts are among the fastest-growing segments due to increasing demand for 100% bio-based, metal-free pretanning systems.

The patented wet-green® technology is also based on a water-only extraction process, fully aligned with circular economy principles by avoiding waste burning and contributing to CO<sub>2</sub> emission reduction.

Olivenleder® technology is adopted by premium brands such as Vitra, BMW, Volkswagen, Škoda, Porsche, Automobili Pininfarina and Patagonia, together with their associated tannery partners. These brands appreciate the unique interaction between olive polyphenols and collagen, particularly the natural dual binding mechanism that ensures softness, performance and skin compatibility.

### **Gallnuts**

Gallnut extract represents a niche but highly specialised segment. Due to limited raw material availability, production volumes remain modest. However, gallnuts offer high tannin content, very light colour and exceptional lightfastness, making them particularly suitable for luxury and specialty leather applications.

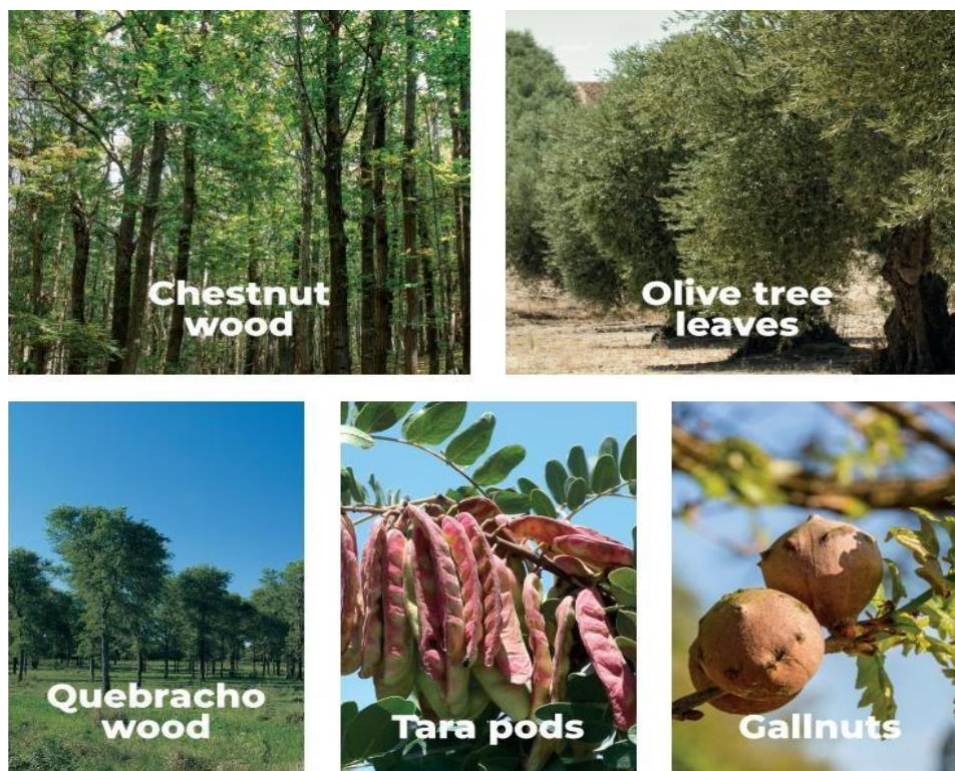


Figure 3: Pictures of the raw materials used for tannin extraction: chestnut wood, olive pruning, quebracho wood, tara pods and gallnuts



Figure 4: Tannin powders: 1. chestnut; 2. quebracho; 3. gallnuts; 4. tara and 5. Olive pruning

*IULTCS Question 3: Silvateam has evolved from being a leather tannin supplier to a diversified production of additives for the food, pharma, animal nutrition and agriculture. Which were the challenges you had for diversification and how much of your production is dedicated to leather (%)?*

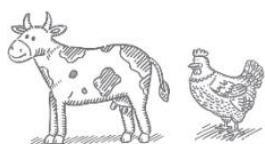
Globally, Silvateam's tannin applications are currently distributed approximately as follows:

- Leather: 42%
- Non-leather applications: 58%

While leather remains a strategic core sector for Silvateam, diversification has been a deliberate and forward-looking choice.

Over the past decade, the leather industry has faced structural headwinds, including progressive contraction in certain segments, intensified competition from synthetic materials — such as PVC- and PU-based faux and “vegan” alternatives — and evolving consumer lifestyles, particularly the strong growth of casual, athleisure and sneakerdriven footwear. At the same time, global demand for natural, bio-based and environmentally responsible solutions has grown significantly across multiple industries. This macro-trend has created new opportunities for tannins as multifunctional polyphenolic platforms beyond their traditional tanning role.

Today, non-leather applications represent a dynamic and expanding segment of our portfolio. Key Growth Areas include:



#### **Animal Nutrition**

Tannins are increasingly recognised as sustainable alternatives to antimicrobial growth promoters (AGPs), supporting gut health, enhancing nutrient absorption and helping reduce methane emissions in ruminants.



#### **Wine and Brewing**

In oenology, tannins serve as natural clarifying agents and play a key role in taste structure, colour stabilisation, astringency modulation and ageing potential. In brewing, they contribute to haze control and improved mouthfeel.



#### **Agriculture**

Tannins are incorporated into biostimulant formulations and fertilizers, promoting plant resilience, improving soil structure and supporting regenerative agricultural practices.



#### **Cosmetics and Personal Care**

Their antioxidant, anti-inflammatory and antimicrobial properties make tannins promising bio-based ingredients in skincare formulations, particularly for protection against oxidative stress and environmental pollutants.

Diversifying beyond leather required substantial transformation:

- Regulatory adaptation, particularly in food, feed and cosmetic sectors
- Technical reformulation and application development, as each industry requires tailored performance characteristics
- Market education, positioning tannins as multifunctional bio-based solutions rather than niche tanning extracts
- Investment in R&D and application laboratories to support customers with formulation expertise

This strategic evolution has significantly strengthened Silvateam’s resilience, reduced dependency on a single industry cycle, and reinforced our positioning as a global supplier of sustainable, high-performance polyphenolic solutions.

Leather remains foundational to our identity and expertise, but diversification ensures long-term growth and stability while unlocking the broader potential of tannins across multiple industries.



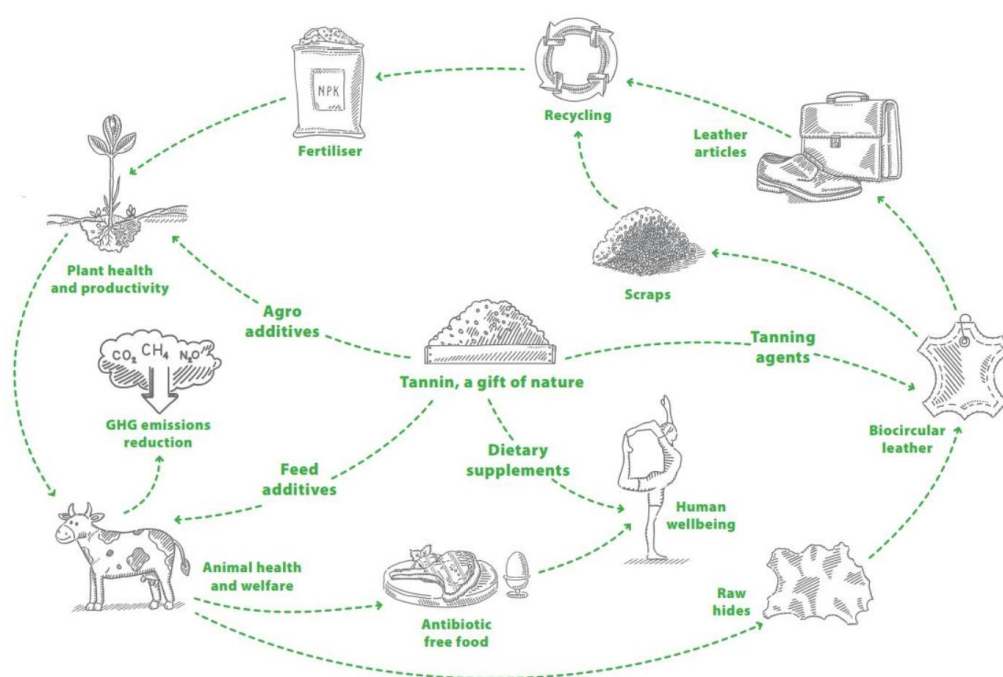


Figure 5: Circularity of the tannins

*IULTCS Question 4: Please give us an overview of the tara production, with history of the production and what the future is (how it will look in 10 years?). Why only Peru produces tara?*

Tara (*Caesalpinia spinosa*) is native to the Andean region of Peru, where it grows naturally up to 3,000 meters above sea level in dry and semi-desert climates. Traditionally, tara pods were used as a natural source of tannins for leather production. Over time, thanks to Silvateam, tara has evolved into a strategic biobased raw material for both leather and food applications.

Peru is today the global hub of tara production, and Silvateam is one of the leading industrial players in this sector, with a modern manufacturing plant in Chilca and a production capacity exceeding 1,600 tonnes per year.

Tara sourcing in Peru combines:

- Wild harvesting in the Andean valleys, providing income to local communities
- Three proprietary Silvateam plantations in Huánuco and Ica, covering approximately 620 hectares

The Huánuco plantation, established in 2002 at 2,500 meters altitude, produces certified organic tara. The Ica desert plantations (established in 2006 and expanded in 2021) demonstrate how tara can successfully grow in arid conditions using microirrigation systems and underground aquifers. Through agronomic research and cultivar selection, Silvateam has significantly improved productivity and sustainability standards over the last decade.

Beyond industrial production, Silvateam's vertically integrated supply chain supports more than 10,000 local families through long-term contracts and Fair-Trade certification, contributing to stable income in rural Andean communities.

Peru remains the only large-scale producing country due to its unique microclimatic conditions — altitude, solar radiation, dry climate and soil characteristics — which are difficult to replicate elsewhere. Trials in other regions, including North Africa, have not achieved comparable commercial results.

Looking ahead, tara production is expected to become even more structured and sustainable. Over the next 10 years, growth will likely focus on improved yields, expanded food applications and further strengthening of Fair Trade and organic sourcing. In this context, Silvateam will continue to play a central role in developing tara as a versatile and sustainable ingredient for global markets.



Figure 6: Tara harvest at Huánuco, Peru, plantation at 2,500 m above sea level

*IULTCS Question 5: How are the tara pods used in the leather industry and which are the other industrial uses? Are there different grades of tara products?*

Tara pods are widely used in the leather industry as a source of vegetable tannins. The tannins are obtained from the pods through a mechanical milling process, without the use of chemical substances. This natural processing method preserves the intrinsic characteristics of the raw material while ensuring high purity and consistent quality. Tara tannin extracts are particularly valued for their light colour and excellent tanning performance. In leather manufacturing, they are mainly used for vegetable tanning and retanning, contributing to fullness, tight grain, and good lightfastness, especially in leathers with pale or pastel colours.

In addition to leather applications, tara derivatives have several other industrial uses. The seeds of the tara pods are processed to produce tara gum, a natural polysaccharide obtained through a mechanical separation operation. Tara gum is primarily used as a thickening, stabilising, and gelling agent in food, pet food, cosmetics, and certain technical applications.

Silvateam also produces a range of tara extracts tailored to different industrial applications, both within the leather sector and beyond, depending on the required performance characteristics. Regarding product grades, different grades of tara products are available, depending on parameters such as purity, colour, tannin content, particle size, and — in the case of tara gum — viscosity. These variations allow manufacturers to select the most suitable product according to specific technical and performance requirements.





Figure 7: Tara trees at the Ica plantation in a desert area, Peru

*IULTCS Question 6: Please give us an overview of the gallnuts production since this extract has limited use, with history of the production and what the future is (how it will look in 10 years?). Which are the unique properties of the gallnut tannins; how the tanned leather looks like and which are the properties?*

Gallnuts have been used for centuries as a natural source of hydrolysable tannins, historically employed in leather tanning, textile dyeing, and even ink production. Today, gallnut extract remains a highly specialised vegetable tannin, produced from galls that develop naturally on certain trees. The production process involves harvesting, drying, and a specific extraction of the galls to obtain a high-purity tannin extract.

Due to the limited and geographically concentrated availability of raw material, gallnut production is relatively small compared to other vegetable tannins. As a result, its use in the leather industry is restricted to selected applications. Looking ahead to the next 10 years, gallnut extract is expected to remain a niche product, primarily dedicated to high-value segments. However, increasing demand for bio-based and sustainable tanning solutions may further enhance its strategic importance in premium markets.

The main property of gallnut extract is its extremely high tanning power, combined with a very light, almost white colour. It also offers outstanding lightfastness and excellent heat resistance compared to most other vegetable tannins. These characteristics make gallnut tannins particularly suitable for producing very light or white leathers with superior stability over time.

Leather tanned or retanned with gallnut extract is typically firm, compact, and finegrained, with a clean and bright appearance. It shows excellent resistance to yellowing when exposed to light and heat, maintaining its original shade and aesthetic quality.

Because of its limited availability and premium characteristics, gallnut extract is mainly dedicated to niche markets such as luxury leather goods and exotic leathers, where performance, appearance, and long-term stability are essential.

*IULTCS Question 7: Your company offers two sustainable solutions with vegetable extracts: Ecotan® and Olivenleder®. Please describe briefly these technologies, products used and how the leather properties are.*

Our company offers two innovative and sustainable tanning solutions based on vegetable extracts: Ecotan® and Olivenleder®. Both technologies are designed to avoid the use of chromium, zeolites, other minerals, as well as synthetic reactive tanning agents such as glutaraldehyde.

#### **Ecotan®**

Ecotan® has been developed with biocircularity in mind. The concept is to support tanneries with unique, tailor-made blends of natural vegetable tannins, enabling the resulting leather to enter multiple biocircular pathways at the end of its useful life cycle, such as:

- Biodegradability
- Biofertilizer
- Biochar

The vegetable extracts (chestnut and quebracho) used for Ecotan® originate from PEFCcertified forests, ensuring responsible and sustainable forest management. Additional extracts include tara powder and olive pruning extracts.

By carefully formulating customised tannin blends, Ecotan® leather achieves high performance while maintaining a fully bio-based tanning system.

If Ecotan® is combined with the patented wet-green® pre-tanning technology, customers can obtain a dual certification: Ecotan® Olivenleder®, further strengthening sustainability credentials and material circularity.

In terms of leather properties, Ecotan® leathers can be produced in various articles, such as footwear, leather goods and automotive, offering good fullness, natural handle and excellent technical performance, while maintaining compostability and circular potential.



Figure 8: Ecotan® Fit for Rebirth, a pioneering 100% biodegradable and recyclable, zerowaste sneaker concept

#### **Olivenleder®**

Olivenleder® is based on the patented wet-green® technology, which uses a liquid extract derived from olive tree pruning — a renewable by-product that would otherwise be burned. The



technology was developed according to the Cradle to Cradle® concept. The olive extract contains natural polyphenols, including oleuropein, which provide two binding mechanisms:

- Hydrogen bonding
- Covalent crosslinking

This dual reaction mechanism is unique among vegetable tannins and enables, for the first time, the production of very soft vegetable-tanned leathers with true Nappa-like softness — including extremely soft garment leathers.

Thanks to the natural crosslinking effect (similar in performance to synthetic reactive tanning agents), Olivenleder® can meet stringent technical requirements, including those of the automotive industry. It is used, for example, in premium vehicles such as the BMW iX and Porsche Taycan, not only for seats but also for instrument panels and door trims.

Olivenleder® is mainly known for its soft Nappa leather types. Most prominent for example in garments at HUGO BOSS and Armani. But also shoe upper and saddlery leather is possible. Essentially, any type and colour of leather can be developed, provided that mineral tanning agents (e.g., chromium or zeolites) and synthetic reactive tanning chemicals, such as glutaraldehyde, are avoided.



Figure 9: BMW iX leather car interior crafted with Olivenleder®

*IULTCS Question 8: Both Ecotan® and Olivenleder® leathers are considered biodegradable and compostable, becoming biofertilizer and/or biodegradable during composting. Please describe the characteristics and properties of these leather products.*

Both Ecotan® and Olivenleder® leathers are designed as vegetable-based tanning systems, free from chrome, metals, glutaraldehyde and any other hazardous substances. These clean formulations are the key prerequisite for their biodegradability in compost.

During composting, the collagen matrix of the leather gradually biodegrades through microbial activity. The absence of heavy metals or persistent synthetic tanning agents ensures that no harmful residues remain in the compost. The process creates a virtuous circular system:

- The CO<sub>2</sub> balance is redirected toward biological consumption.
- Tanned collagen fibres, which are rich in nutrients such as organic nitrogen, contribute to gradual nutrient release into the soil.

- The slow degradation allows controlled nitrogen availability, supporting plant growth over time.

Ecotan® and Olivenleder® leathers can also be transformed into organic fertilizer — certified for use in organic agriculture — through a chemical hydrolysis process, offering several advantages:

- Collagen fibres act as a natural source of nitrogen for the soil.
- Collagen hydrolysis can generate amino acids such as hydroxyproline, which functions as an effective biostimulant.
- Vegetable tannins contained in the leather may provide additional protective effects for plants, contributing to natural resilience against external stress factors. This process creates a value-added end-of-life solution, where leather waste is not simply disposed of but converted into a beneficial soil amendment.



Figure 10: Vegetable-tanned leather transformed into biofertilizer for organic farming

These sustainable technologies allow the production of leathers which combine the advantages of being compostable and bio-based with consistently high technical and aesthetic performance throughout their service life:

- Excellent mechanical strength and durability
- Softness and flexibility (particularly for Olivenleder®)
- Lightfastness and heat resistance
- Suitability for fashion, luxury, automotive, footwear, and leather goods

In summary, Ecotan® and Olivenleder® combine performance and sustainability by offering high-quality tannin-based leather articles that can safely return to the biological cycle at the end of their life, contributing to circular economy principles.

*IULTCS Question 9: What is the technology behind the Olivenleder®? Is just an extraction of the olive pruning or it has chemical modification?*

The wet-green® process used to create the Olivenleder® pre-tanning agent from olive pruning is essentially a simple water-based extraction. It is so clean, that the Dermatest® seal of approval has rated it EXCELLENT. Tested on the human skin for skin sensitivity with a certified 100% Biocontent.



*IULTCS Question 10: Looking ahead 5 (or 10?) years from now, how do you predict will be the evolution of the use of the natural tannin materials in leather? Are the other industrial uses of tannins consuming most of the products that use in the tanneries will be reduced?*

Today, natural tannins are widely used in leather making to fine-tune and enhance the final properties of leather. With the growing shift toward sustainability, the green leather solutions we offer present a significant opportunity. This is especially true for brands and tanneries that take responsibility for their actions. With abundant raw material sources such as chestnut and olive, the potential is enormous.

For example, the amount of olive leaves available each year could easily cover around 40% of global leather production. And when using the entire olive tree pruning, as we currently do at Silvateam, the potential becomes even greater. By valorising by-products from the olive harvest — and therefore avoiding burning and CO<sub>2</sub> emissions — we enable a truly circular model. In other words, this is a case of tanning a by-product with a by-product: a perfect example of circular economy. It also offers the leather industry a powerful opportunity to communicate to brands and consumers that leather is a natural material, not a plastic.

Other industries are increasingly recognising the unique and positive properties of tannins, and their use is growing. Sustainable forest stewardship - supported by certification schemes such as PEFC - ensures continuous forest regeneration and responsible biomass management. In regions where structured forest management is implemented, tannin production can be fully aligned with long-term ecological balance.



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## IULTCS NEWSLETTER



## Newsleather

Stay curious, informed and connected

Edition 14, 2025

## Welcome

This is the fourteenth edition of our scientific newsletter, dedicated to providing the latest updates on research, regulatory developments, technology, and standard methods in the leather industry.

**NOTE: This newsletter is in English, Italian, Spanish, Portuguese and Turkish. One version after the other.** [LFJ Editor's note: For other language versions please visit [www.iultcs.org](http://www.iultcs.org)].

In this issue, we feature an interview with Mr. Santo Mastrotto, Honorary Chairman and Chief Executive Officer of Gruppo Mastrotto S.p.A. in Arzignano, VI, Italy.

IULTCS appreciates the collaboration of Mr. Santo, an active supporter of AICC (Italian Leather Chemists Association) and IULTCS. Mr. Santo has been one of the most active tanners in Italy and his work transcends through many generations and has global ramifications.

We extend our sincere thanks to Mr. Santo for his valuable contributions to IULTCS Newsleather.

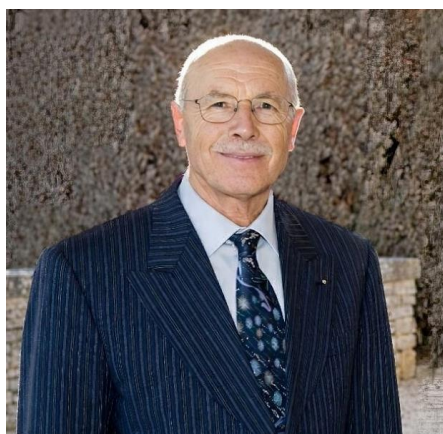
Please share your comments and suggestions to [secretary@iultcs.org](mailto:secretary@iultcs.org)

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Kind regards,  
Dr. Luis A. Zugno, editor

## IULTCS INTERVIEW

## Honorary Chairman and Chief Executive Officer of Gruppo Mastrotto S.p.A. in Arzignano, VI, Italy



Mr. Santo Mastrotto was born in 1938 in Nogarole Vicentino, in the upper Chiampo Valley. As a young man, he initially planned to emigrate to Canada, but when the country closed its immigration quotas, Venezuela became the alternative destination. In order to prevent Santo from emigrating there, his father, Arciso Mastrotto, decided in 1958 to open the family's first tannery in Arzignano together with his children.

From that moment on, Santo devoted his life to a Group that has since grown steadily in Italy and around the world. In 1990, driven by a desire to diversify and invest in forward-looking and sustainable activities, he promoted the creation of Midac, a company specializing in batteries for starting and traction applications.

He was deeply involved in AICC for many years and served as its President during the 1996–1998 term. A pioneer of the Group's international expansion, Santo also led the construction and start-up of its first tannery outside Italy. In 1999, this initiative resulted in the establishment of what is now Mastrotto Brasil.



Gruppo Mastrotto is an internationally renowned tanning group, with a history of almost 70 years and roots in the district of Arzignano (Vicenza). Founded in the 50s thanks to the entrepreneurial vision of the brothers Bruno and Santo Mastrotto, the Group has developed over time a global presence and constant growth, based on quality, innovation and specialization. Today, the Group continues its evolutionary path by strengthening its vision and positioning in the market. Collaborating with leading brands in interior design, fashion, automotive, nautical and aviation sectors, Gruppo Mastrotto has consolidated a distinctive position in the premium and luxury segment, offering items appreciated for their reliability, style and performance. The commitment to sustainability, continuous research and advanced processes defines the Group's identity and its vision of responsible development. A path that finds expression in the payoff Leather Forward, a symbol of a constant evolution oriented towards the future of leather and design. <https://www.mastrotto.com/en>

*IULTCS Question 1: Mr. Santo, could you please provide a brief overview of the history of Gruppo Mastrotto's first tannery, including its origins and initial activities?*

Mr. Santo Mastrotto was born in 1958. Ours was a peasant family, five sons and a daughter, my brothers Bruno and Angelo worked as employees in tanneries in Arzignano and in the evening at dinner, my brother Bruno told us that we earned well with those activities that they then called leather goods. Our father, who was trying to give his children an opportunity, looked for partners and so the Aurora Tannery was born, practically a house in the center of Arzignano, starting from nothing, with the courage to feel like a united family, all the brothers involved, all working day and night.



Fig. 1: Headquarter of the Gruppo Mastrotto in Arzignano, VI, Italy

*IULTCS Question 2: The book Dalla Pelle al Cuore presents 60 stories that clearly highlight how passion, courage, and family values have shaped Gruppo Mastrotto. Could you elaborate on the challenges of preserving these values over the years?*

Three generations with common factors, a lot of passion and a lot of desire to do. With my brother Bruno and our families, the utmost respect for the company, always put first, even in the face of personal interests. Many times, the courage to take risks, to do new things, to experiment and change. And above all, luck and the ability to have extremely valid collaborators at their side, who many times have made the difference.

*IULTCS Question 3: In the past, a tannery's sole task was to produce leather. Today, the process has become far more complex, as the waste once discarded must now be transformed into valuable by-products. This shift has significantly increased operational complexity. How is Gruppo Mastrotto addressing these changes?*

This is one of the challenges where excellence can emerge. For a long time, grasping these changes and personally feeling the need to improve the environment where I live and where my family lives, I have focused on three commandments, anyone who knows me knows how important they are to me. First, in the production process it is necessary to research and use chemicals that have the least impact on the environment and that allow less use of water and energy. Second, the products must go into the skin. Third, the leather waste generated in the various stages of processing must be used and recycled, as is now the case in the vast majority of cases.



Fig. 2: Overview of one of the tanneries of the Gruppo Mastrotto in Arzignano, VI, Italy

*IULTCS Question 4: Please mention the biggest changes you have seen in the leather industry during your lifetime, particularly in Arzignano.*

It's not just the tanning industry that has changed, everything has changed. Everything, even now that we are talking about it, is profoundly changing. The globalization of recent decades has reshuffled the cards, and nothing is the same as before. Arzignano has changed, there are larger and better structured companies, those who produce chemicals for leather processing and those who produce tannery machinery have grown. Today we have a flagship, a very efficient public purification plant, there is a company that transforms our by-products into high-performance materials. We have come a long way, but I think we must continue to question ourselves, it seems to me that there is a good climb ahead of us and keeping up with the speed of market evolution requires a lot of effort.



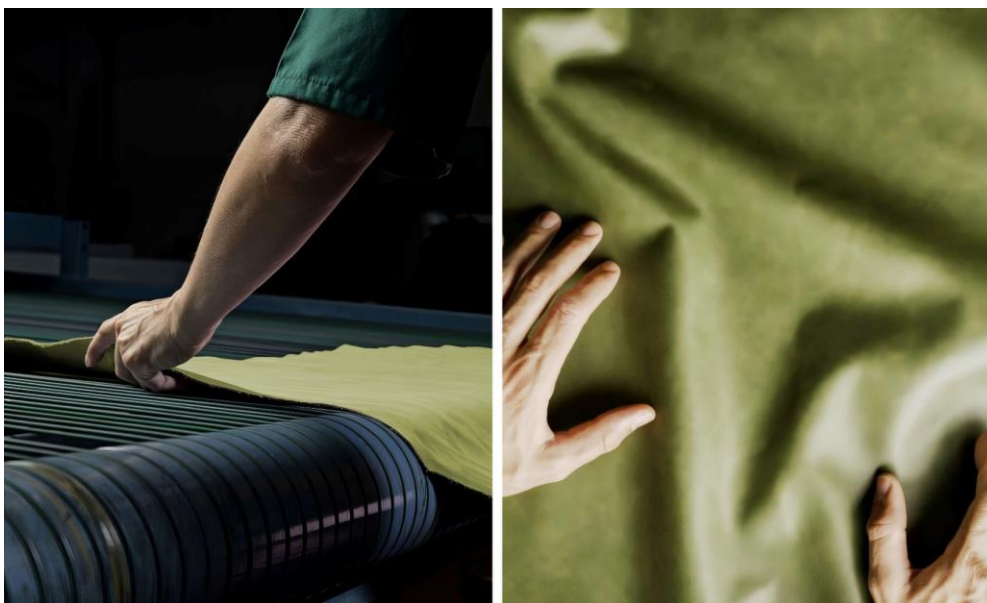


Fig. 3: Leather production made with art and technology

*IULTCS Question 5: You developed the innovative process of suede without intermediary drying. Please describe how it was invented what you did to keep as a secret for many years.*

We produced grain leather. We started collaborating in 1965 with Mr. Baschirotto of Bassano, in Bassano the production of suede was very developed. He brought us into this business but at that time suede was produced in two stages, therefore in drums to make the intermediary crust and then in drums for dyeing. With the experience of the grain leather, I wondered why such a long process, and I started to do scab tests with the grain. At the beginning it came out to be a very poor product but by insisting I managed to produce a good suede with a direct (one step) process. I personally took care of the retanning and therefore not sharing this discovery with anyone and continuing to do everything by myself. I managed to keep this technology only for us, as a secret for eight years. Those were the years of miniskirts, boots, all in suede. We were thus able to produce faster and at lower costs in a market that mainly demanded suede. It was a great time in my life.

*IULTCS Question 6: Innovation has consistently played a significant role in your company's progress. What steps were taken to develop an innovative culture? What obstacles did you encounter when introducing new technologies?*

In budgets it is always necessary to provide companies with economic availability to do research and development. The activity and support of laboratories today is indispensable for any tannery. But I would like to dwell on the importance of being close to customers when they share their expectations with the tannery, generally always improving, in various aspects, qualitative, economic and above all today of sustainability, this collaboration pushes the organization to innovate. The tanneries of Arzignano can count on the help of the supply chain and successfully develop projects and products. I have not encountered resistance to innovation; on the contrary it generally becomes a stimulus for everyone.



Fig. 4: Analytical equipment for process control

*IULTCS Question 7: You participate actively at AICC, attending the meetings and speeches. Why is it important to participate in AICC (Italian Leather Chemists' Association)?*

AICC, especially today, has become the only opportunity for our sector, in Italy, to bring together in a single context, technicians and experts, tanneries, even competitors, local and international chemical product companies, companies that invent and produce machinery and plants for tanneries. This type of confrontation and I hope for collaboration are very valuable. They have already given important results in the past, I still remember when I was president in '97, we created two working teams involving various experts from the AICC, one group studied the wet part, and one group studied the finishing part. It was precisely in this situation that we were able to develop water-based finishing technology, replacing solvents. It was one of my greatest satisfactions.

*IULTCS Question 8: In your view, what factors have contributed to making the Arzignano area the world's leading leather center? Why has Arzignano achieved this status instead of another location?*

Certainly, as mentioned before, the fact that the entire supply chain has developed at the same time, therefore chemical, mechanical, tanning and I would include water purification and exploitation of tanning production residues, in this almost harmonious growth everyone has benefited from transversal collaboration. In addition, the processing of leather also maintains an artisan aspect with the ability to do well and make beauty, especially important for the world of fashion, a natural characteristic for Italians. But also, in technical sectors such as the production of automotive leathers, the tanneries of Arzignano have proven to be very valid and offer first-class products to international customers. My personal applause goes to the work culture that has distinguished the people of our valley for decades. Desire to do, generosity towards one's profession and stubbornness in wanting to achieve results. This, I think, is one of the most important factors.

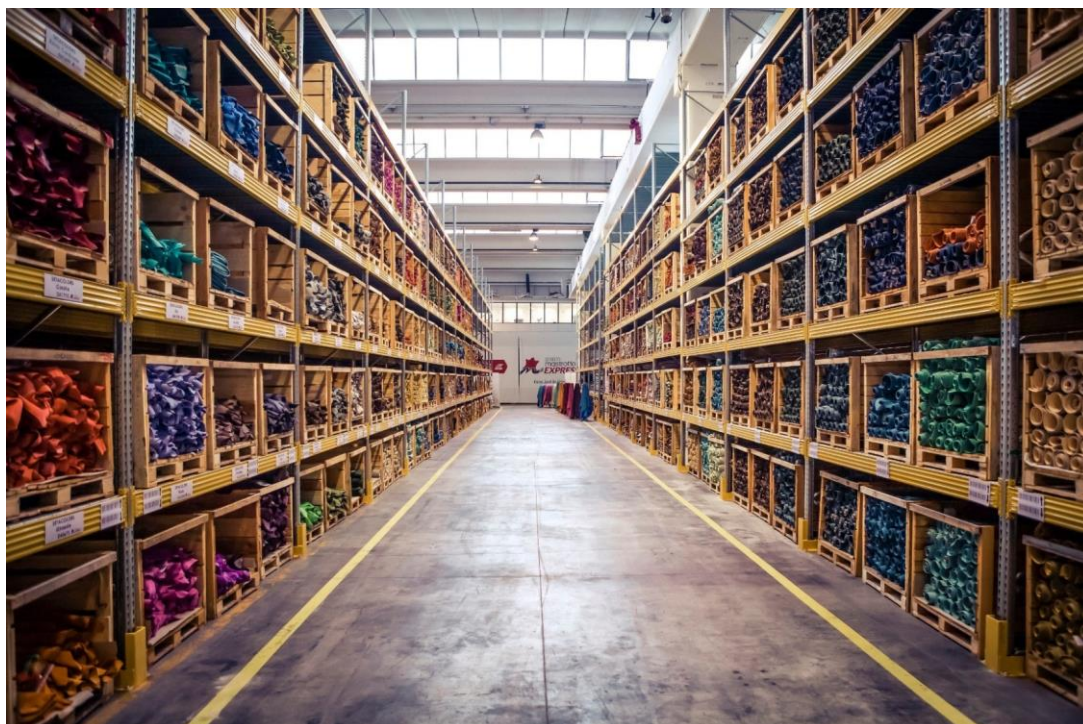


Fig. 5: Gruppo Mastrotto Express offers leathers in 1,600 colors all the time; available to ship within 48 hours, this is a “just in time” innovative service

*IULTCS Question 9: What counsels would you offer to newly appointed leather technicians commencing their professional journey at Gruppo Mastrotto?*

I would advise new tanning technicians to build solid foundations, without relying only on "recipes": understanding the material, the process and their interactions really make a difference in daily work. Higher education, from technical institutes to Superior Technological Institutes (ITS) courses, is a fundamental step in acquiring method, technical language and a structured vision of the sector, as well as the ability to connect theory and practice. Once in the company, it is important to carefully observe production, listen to those working on the line and understand the real constraints of time, systems and costs. Taking systematic notes and reflecting on mistakes and results allows you to transform experience into competence. Rigor, curiosity and professional transparency are essential: in the tanning industry, growth is gradual and reputation remains one of the most important assets. Everything today is very fast; everything changes and keeping up with technological innovations is already a challenge. You must produce very well, spend little and constantly reduce the impact on the environment. It is important to be open, never to fall into arrogance, because someone, somewhere, is probably already doing better than us. Only by being predisposed to question ourselves can we produce well and be competitive. But I would also say that it is a beautiful job, where people can really enhance their skills and creativity because in the tannery there are a hundred different ways to work the leathers and the technician is the architect of the success or failure of the process.





Fig. 6: Automotive Leather cutting facility

*IULTCS Question 10: Mr. Santo, you have witnessed profound transformations in the Italian leather industry. How do you envision the future of the leather sector over the next decade, both at Gruppo Mastrotto and across Italy?*

First of all, we need to work on communication, the understanding of leather today, especially by the new generations, is often incorrect. There is a lot of fake news and it seems to me that there is not enough effort to say in the proper way how things really are, remembering that leather is the oldest form of circular economy, explaining that leather comes from the slaughter of animals, slaughter that takes place to feed people, that leather is a durable and healthy material, No animal is killed to provide leather to our tanneries. Personally, I believe that the future of tanneries, in general, also depends on whether we are able to convey these messages. And in the age of communication, we risk losing this appointment!



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