

TATTOO AS A WAY OF FINISHING VEGETABLE-TANNED CRUST LEATHER

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ABSTRACT. Leather embellishment is a rich art form that can create diverse functional products. Traditional and modern techniques manipulate leather fibers to create precise designs and require careful handling due to leather's intricate structure. This study focused on optimizing and evaluating the compatibility of tattooing inks and application techniques with vegetable-tanned crust leather. Two commercially available inks, Dynamic Ink Triple Black 240ml and Super Black Ink, were assessed for pH and color fastness to rubbing, and Dynamic Ink Triple Black 240ml demonstrated superior color fastness. Next, the conditions for applying the tattoo were optimized, and its effect on the leather structure and properties was studied. The impact of cleaning alcohol concentration, needle speed, and the number of finishing agent coats on color fastness to rubbing (dry and wet) characteristics of tattooed leather was optimized using Design-Expert version 13. It indicated that higher cleaning alcohol concentration and needle speed negatively affected color fastness, while more coats of the finishing agent improved it. Post-tattooing, the tensile strength slightly decreased from 17.8 N/mm², to 17.3 N/mm², elongation reduced from 28.40% to 27.70%, and tear strength marginally decreased from 25.0 to 24.7 N/mm. Abrasion resistance tests showed slight damage to the leather after tattooing, indicating some weakening of the surface structure. Despite these changes, the leather maintained high durability and flexibility. FTIR analysis revealed the formation of new and modification of existing chemical compounds in the collagen structure as a result of the interaction of ink components with leather. Overall, this study demonstrates the feasibility and durability of tattooing vegetable-tanned cowhide crust leather using Dynamic Ink Triple Black 240ml, providing optimal results in terms of color fastness and minimal impact on the leather's structure and properties.

KEYWORDS: finishing, vegetable-tanned leather, tattoo, tattoo ink

TATUAJUL CA MODALITATE DE FINISARE A PIELII CRUST TĂBĂCITE VEGETAL

REZUMAT. Înfrumusețarea pielii este o formă de artă cu ajutorul căreia se pot crea diverse produse funcționale. Tehnicile tradiționale și moderne manipulează fibrele de piele pentru a crea modele precise și necesită manevrare atentă datorită structurii complexe a pielii. Acest studiu s-a concentrat pe optimizarea și evaluarea compatibilității cernelurilor de tatuaj și a tehnicilor de aplicare cu pielea crust tăbăcită vegetal. S-au evaluat două cerneluri disponibile comercial, Dynamic Ink Triple Black 240ml și Super Black Ink, în ceea ce privește pH-ul și rezistența culorii la frecare, cerneala Dynamic Ink Triple Black 240ml demonstrând o rezistență superioară a culorii. În continuare, s-au optimizat condițiile de aplicare a tatuajului și s-a studiat efectul acestuia asupra structurii și proprietăților pielii. Impactul concentrației alcoolului de curățare, al vitezei acului și al numărului de straturi de agent de finisare asupra caracteristicilor de rezistență a culorii la frecare (uscată și umedă) a pielii tatuată a fost optimizat folosind Design-Expert versiunea 13. A rezultat că o concentrație mai mare a alcoolului de curățare și viteza acului au afectat negativ rezistența culorii, în timp ce mai multe straturi de agent de finisare au dus la îmbunătățirea acesteia. După tatuare, rezistența la rupere a scăzut ușor de la 17,8 N/mm² la 17,3 N/mm², alungirea s-a redus de la 28,40% la 27,70%, iar rezistența la sfâșiere a scăzut marginal de la 25,0 la 24,7 N/mm. Testele de rezistență la abraziune au arătat o ușoară deteriorare a pielii după tatuare, indicând o oarecare slăbire a structurii suprafeței. În ciuda acestor modificări, pielea și-a menținut o durabilitate și o flexibilitate ridicate. Analiza FTIR a relevat formarea de compuși chimici noi și modificarea celor existenți în structura colagenului, ca urmare a interacțiunii componentelor cernelii cu pielea. Per total, acest studiu demonstrează fezabilitatea și durabilitatea tatuării pielii crust bovine tăbăcite vegetal folosind Dynamic Ink Triple Black 240ml, oferind rezultate optime în ceea ce privește rezistența culorii și un impact minim asupra structurii și proprietăților pielii.

CUVINTE CHEIE: finisare, piele tăbăcită vegetal, tatuaj, cerneală pentru tatuaj

LE TATOUAGE COMME TECHNIQUE DE FINITION POUR LA CROÛTE DE CUIR AU TANNAGE VÉGÉTAL

RÉSUMÉ. La décoration du cuir est un art riche permettant de créer une grande variété de produits fonctionnels. Les techniques traditionnelles et modernes manipulent les fibres du cuir pour créer des motifs précis et requièrent une grande précaution en raison de sa structure complexe. Cette étude s'est concentrée sur l'optimisation et l'évaluation de la compatibilité des encres de tatouage et des techniques d'application avec la croûte de cuir au tannage végétal. Deux encres disponibles dans le commerce, Dynamic Ink Triple Black 240 ml et Super Black Ink, ont été évaluées quant à leur pH et leur résistance au frottement. L'encre Dynamic Ink Triple Black 240 ml a démontré une résistance supérieure. Ensuite, les conditions d'application du tatouage ont été optimisées et son effet sur la structure et les propriétés du cuir a été étudié. L'impact de la concentration d'alcool de nettoyage, de la vitesse de l'aiguille et du nombre de couches de finition sur la résistance au frottement (à sec et à l'eau) du cuir tatoué a été optimisé à l'aide du logiciel Design-Expert version 13. Les résultats ont montré qu'une concentration d'alcool de nettoyage et une vitesse d'aiguille élevées affectaient négativement la résistance des couleurs, tandis qu'un plus grand nombre de couches de finition l'améliorait. Après tatouage, la résistance à la traction a légèrement diminué, passant de 17,8

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N/mm² à 17,3 N/mm², l'allongement a été réduit de 28,40 % à 27,70 % et la résistance au déchirement a légèrement diminué de 25,0 à 24,7 N/mm. Les tests de résistance à l'abrasion ont révélé de légers dommages au cuir après tatouage, indiquant un affaiblissement de sa structure superficielle. Malgré ces modifications, le cuir a conservé une durabilité et une souplesse élevées. L'analyse FTIR a révélé la formation de nouveaux composés chimiques et la modification de composés existants dans la structure du collagène, suite à l'interaction des composants de l'encre avec le cuir. Globalement, cette étude démontre la faisabilité et la durabilité du tatouage du cuir de vachette tanné végétal (croûte) avec l'encre Dynamic Ink Triple Black 240 ml, offrant des résultats optimaux en termes de tenue des couleurs et un impact minimal sur la structure et les propriétés du cuir.

MOTS-CLÉS : finition, cuir tanné végétal, tatouage, encre de tatouage

INTRODUCTION

Recently, there has been significant interest in leather products across the global market due to their durability, versatility, and timeless appeal [1]. As per Grand View Research, the global leather goods market was valued at USD 242.85 billion in 2022 and is expected to grow at a CAGR of 6.6% from 2023 to 2030 [2]. In the textile and apparel sector, leather is utilized in 13.4% of leather goods, 13.4% of automobile interiors, 13.3% of upholstered furniture, 11.4% of clothing, 1.8% of other products, and 37.8% of footwear [3]. Maintaining a compound annual growth rate in the leather goods industry and fostering consumer desire for leather goods can be strongly correlated with the effective utilization of leather embellishment techniques to enhance its aesthetics, durability, functionality, and sustainability [4].

Leather embellishment is a craft that blends skill, creativity, and enhance the look and utility of leather goods. It has a rich history, with civilizations like the Egyptians, Greeks, and Romans pioneering early tanning techniques. The practice serves dual roles: creating practical and ornamental items, and offering a diverse array of stunning pieces that elevate aesthetics [5]. Traditional methods such as tooling, embossing, dyeing, edge painting, and background coloring are utilized, while modern leather embellishment incorporates innovation and technology like laser cutting and digital tools to transform traditional materials into unique, practical pieces [6].

As per [7], challenges in leather embellishment arise from the complex nature of leather, including its thickness, density, and moisture content. Traditional leather embellishment techniques have limitations in

scalability, precision, individualization, environmental impact, and customization because of the variability of leather material, water content, surface topography, leather fiber density, and anisotropy. Edge painting involves the application of pigments to leather, facing challenges such as adhesion, flexibility, penetration, color retention, and material compatibility. Modern leather embellishment techniques encounter challenges such as material interactions, dimensional accuracy, environmental impact, and economic feasibility. These challenges are caused by excessive heat from laser interaction, which can damage collagenous structures in leather, too much pressure, which can cause tearing or fraying, and variations in fiber density, tanning technique, and water content. Laser finishing, while accurate, carries the risk of damaging collagen fibers due to high heat. These problems present an opportunity to explore the potential integration of tattooing technology into leather embellishment. It is a form of body modification that consists of inserting tattoo ink, dyes, and pigments into the dermis layer of the skin, either permanently or temporarily [8].

Tattooing on natural leather combines personalization, individualization, creativity, cultural significance, and versatility, making it an attractive choice for leather decoration for those who appreciate its unique characteristics [9]. This finishing method is best suited for vegetable-tanned cowhide, which has undergone basic physical and chemical processes and mechanical operations before repainting. The sufficiently high level of structure formation of the material, its physical and mechanical properties (strength, thickness), and the absence of a surface coating create favorable conditions for the penetration and fixation of tattoo ink. To

tattoo tanned leather, begin by cleaning the surface with rubbing alcohol, sketch the design, dip a needle in ink, and let it set for 1 to 2 days. Once the ink has set, wipe off any excess with a clean cloth. Repeat the process for any additional designs or details, and the leather tattoo should now be permanent and ready to show off. However, according to the authors' data, systematic scientific studies on tattooing on vegetable-tanned crust leather and products made from it have not been conducted. Therefore, it is important to integrate tattoo technology into leather finishing, thereby creating a space where artisans can produce highly personalized and expertly crafted leather goods. This study aimed to optimize the tattooing technique applied to vegetable-tanned crust leather while evaluating its effects on structural integrity and mechanical properties, in order to expand its potential for artistic and functional customization without compromising material performance.

EXPERIMENTAL

Materials and Methods

Materials

Vegetable-tanned crust leather: In this study was vegetable-tanned crust leather obtained from medium-weight mature cow hides (25–35 kg green-salted weight), chosen for their well-developed and compact fiber structure. The thickness was controlled at 1.4–1.6 mm, corresponding to firm belt-grade or structured upper leather with a dense full-grain surface. This type of leather was selected because it allows consistent needle penetration and stable pigment retention, reducing excessive ink spreading that can occur in softer upper leather or the limited penetration typical of thick sole leather.

Tattoo Ink: Commercially available Dynamic ink triple black 240ml from (Dynamic Color Co. America) and Super black inks from (Nocturnal Ink / Eternal Ink, America).

Auxiliary Materials: Stencil paper, paper towels, gauze, wiping cloths, adhesive tape, and disposable gloves were purchased from a

tattooing instrument supplier in Bahir Dar City, Ethiopia. A glycerin-based stencil transfer gel was used to adhere the design to the leather surface. A mild antibacterial soap was applied for surface cleaning (degreasing and hygienic preparation) prior to tattooing. Additionally, 70% v/v ethanol (C₂H₅OH) for disinfection and an oil-based leather conditioner (Belpoline) for post-tattoo surface lubrication were procured from tattoo supply vendors in Bahir Dar City and Addis Ababa, Ethiopia.

Equipment: Coil tattoo machine with 6,000 rpm Tattooing was performed using a rotary tattoo machine (Dragonhawk Tattoo Supply, Country: China) powered by a regulated power supply. Needle configurations were selected according to the design requirements (lining and shading). Operational parameters, including voltage and needle depth, were maintained consistently throughout the experiments to ensure reproducibility.

Methods

The experimental design comprised three phases, with Phase I assessing two commercially available tattoo inks using five replicate specimens per group (n = 5) to ensure analytical reliability. The evaluation targeted exclusively the abrasion resistance of the applied ink film on vegetable-tanned crust leather. Using the Krok rubbing fastness scale, the test quantified pigment fixation durability under mechanical rubbing. All test specimens were cut from the butt region of a single vegetable-tanned crust leather to minimize variability associated with topographic differences. The butt region was selected due to its relatively uniform fiber density and mechanical properties. Phase II involved optimizing tattoo ink compatibility and application techniques on vegetable-tanned crust leather. In phase III, the effectiveness of tattooing on the structural integrity and mechanical properties vegetable-tanned crust leather was examined. Statistical analysis was performed using one-way ANOVA at a significance level of p < 0.05.

Ink Selection

Commercially available Dynamic Ink Triple Black 240ml and Super Black Ink were used in this study. No formulation or chemical composition analysis of the inks was performed. The inks were selected based on their professional use and availability in the local market. The pH of the inks was measured using universal indicator paper (pH range 0–14), and measurements were performed in triplicate for each ink. The pH of the leather itself was not measured; only literature values for vegetable-tanned crust leather were referenced.

Application Technique

Based on literature [10-12] and pre-trial experiments, a three-step tattooing procedure was applied to vegetable-tanned bovine crust leather. In this study, three basic steps were followed. The steps included: material preparation, stencil transfer, and ink application.

Preparing Materials

Leather surfaces were cleaned using a mild antibacterial soap solution and

subsequently wiped with 70% (v/v) ethanol to remove dust, surface oils, and potential microbial contaminants; after drying, a thin layer of oil-based leather conditioner (Belpoline) was applied to maintain flexibility and prevent dehydration. Stencils were transferred using a glycerin-based stencil transfer medium, positioned accurately, and secured manually with light, uniform pressure to prevent displacement during tattooing. The tattoo design was applied using a rotary tattoo machine powered by a regulated power supply; a 5RL round liner needle was used for outlining, solid fill areas were executed with a 9M1 magnum shader, and shading was performed using a 7M1 magnum shader in controlled circular and pendulum motions to achieve smooth gradient effects. Operational parameters were standardized, with voltage maintained between 7–9 V and needle protrusion depth controlled at approximately 1.5–2.0 mm (depending on leather thickness); multiple controlled passes were performed as necessary to ensure adequate pigment deposition while avoiding over-penetration and preserving the structural integrity of the leather substrate.

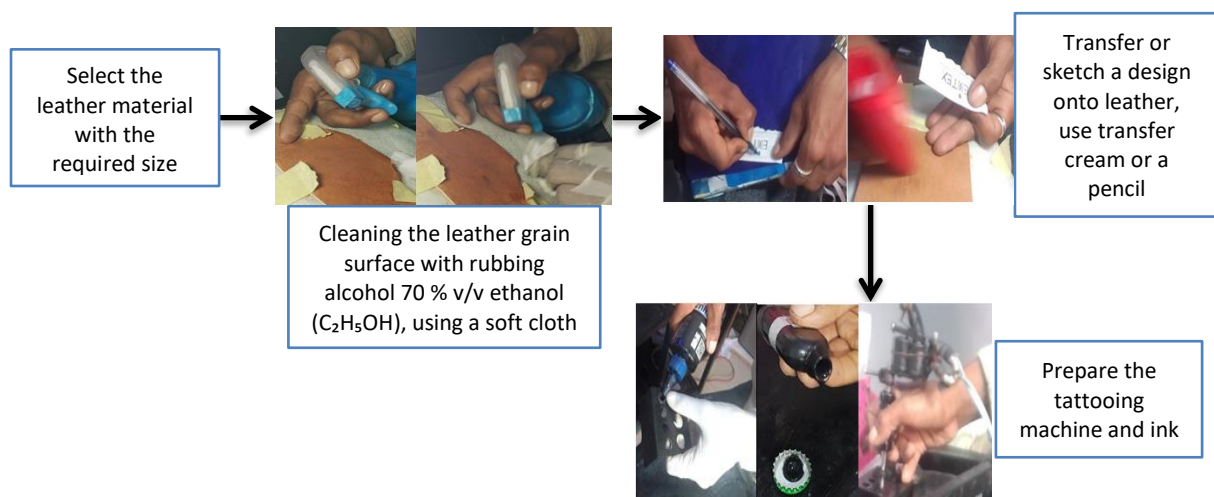


Figure 1. Material preparation

Tattooing Process

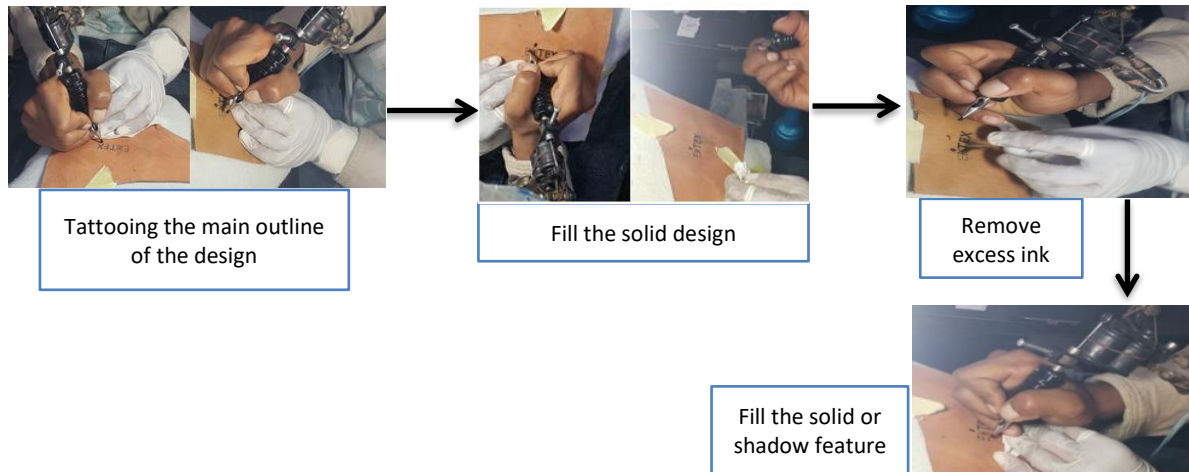


Figure 2. Tattooing process steps

Finishing Process

During the finishing stage, the leather surface was cleaned using green soap, a mild antibacterial soap, widely used in leather care and tattoo practice; it gently cleans the surface

and removes residual ink without damaging the vegetable-tanned crust leather. Antibacterial soap ensures hygiene by reducing microbial contamination on the leather surface after tattooing.

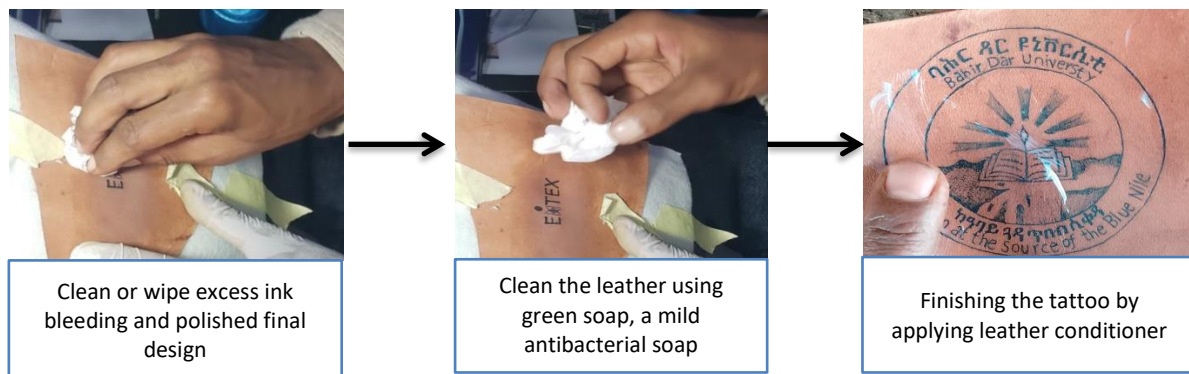


Figure 3. Tattooing finishing process steps

Colorfastness to Rubbing (Crock Meter)

Colorfastness to rubbing was tested using the color fastness to rubbing CrockMaster model 670; weight to produce 9N removable crank counter serial number: 670/19/2127 test ISO 20433:2024/IULTCS/IUF 452.

Experimental Procedure

This section describes the experimental steps followed in this study, including leather sample preparation, stencil transfer, tattoo application, and finishing procedures. The

focus was on evaluating the practical application of commercially available inks on vegetable-tanned crust leather. After identifying the factors affecting the tattooing of vegetable-tanned crust leather, the upper and lower levels of each factor were determined based on previously published literature [13, 14] and the results of pre-trial experiments. The literature provided guidance on typical operational parameters, while the pre-trial tests allowed practical adjustment to the specific leather type used in this study. The researchers selected pre-treatment (cleaning), needle speed, and post-treatment (sealing)

methods as the main factors to enhance color fastness to rubbing and protect the tattoo from wear and tear. Ink consumptions are the same or constant. Pre-treatment (Cleaning) rubbing alcohol 70 % v/v ethanol (C₂H₅OH), concentration (ml) lower level 5% (5ml) and higher level is 10% (10 ml). The applied volume was controlled based on leather sample area (5 mL and 10 mL per 10 cm² of leather). Needle speed (cycles/second) is lower level 14 and higher level 16. Finishing agent number of coats was practiced from 1 to 3 coats. Based on literature and pre-trial experiments, this range is considered optimal for balancing protection and preventing surface damage. Tattooing was performed using a rotary machine fitted with a round liner needle (size 10) at 6–8 V, ensuring precise and uniform penetration into the leather surface. Experiments were conducted under strictly controlled conditions with a Belpoline air conditioner to maintain stable temperature and humidity, minimizing variability in ink performance. Designs were transferred using a stencil method, guaranteeing accurate, reproducible, and well-defined image placement across all specimens. Design Expert 13 software, employing Response Surface Methodology (RSM) with a Box-Behnken design, was used to design the experiment and analyze the results.



Figure 4. Tactile examination of leather before tattooing (A) and after tattooing (B)

Tensile Strength

The tensile strength of tattooed and non-tattooed leather samples was studied according to the ASTM D2209 tensile testing method, fitted with ISO 3376 using a tensile strength tester with model number TENSOLAB1000, type 2511A, serial number: 1064/2013.

The Effect of Tattooing on the Leather Structure and Mechanical Properties

Organoleptic Examination of the Leather

An organoleptic examination of the leather was conducted before and after tattooing. This assessment included both tactile and visual evaluation in order to comprehensively determine the effect of the tattooing process on leather quality.

Visual Examination

The visual assessment focused on determining the clarity and sharpness of tattooed lines, the absence of blurriness or feathering, uniformity of ink distribution, consistency of color intensity, and smoothness of shading transitions. Particular attention was given to identifying any ink diffusion into surrounding leather fibers, surface distortion, or disruption of the natural grain structure.

Tactile Examination

Running fingers over the surface of the leather to detect any irregularities that may not be immediately visible. It involved manual inspection of the leather surface to evaluate grain smoothness, flexibility, surface integrity, and the presence of any roughness, stiffness, cracking, or structural damage.

Elongation

Leather elongation was measured through a tensile test using a tensile strength tester model number TENSOLAB1000, type 2511A, serial number: 1064/2013. This test stretches a sample with a controlled force until it breaks, recording the force and deformation (elongation) throughout the process.

Tear Strength Test

An ASTM D2261 tear strength testing machine fitted with an ISO 3376 using a tensile strength tester with model number TENSOLAB1000, type 2511A, serial number: 1064/2013 was used to measure the tear strength of vegetable tanned cowhide crust leather.

Abrasion Resistance

The abrasion resistance of tattooed and non-tattooed vegetable-tanned leather was tested using Martindale abrasion test machine STM 633;220/230 VAC power supply; LCD digital counter; standard specimen holder 850 mm; weight 56 kg (serial No. 633-9-1518) year of Mfg. 2018 with ES ISO 17076-2:2012 Martindale ball plate method.

Fourier Transform Infrared Spectroscopy (FTIR)

The chemical composition and the structure of collagen of the leather sample were measured using an FTIR machine FTIR analysis (Jasco FT/IR-6600, BiT) according to the method (BIS, 2007). Leather samples were

cut into 5 × 5 mm pieces from the tattooed and un-tattooed regions. Samples were gently cleaned with ethanol to remove surface residues, and then dried under ambient conditions. FTIR spectra were recorded directly on the dried pieces without further chemical treatment.

RESULTS AND DISCUSSION

Ink Selection

Commercially available Dynamic Ink Triple Black (240 mL) and Super Black Ink were selected for this study. No formulation or chemical composition analysis of the inks was performed. Both inks are widely used in professional tattoo practice and readily available in the local market. They were chosen to evaluate practical performance (pH, color fastness to abrasion) on vegetable-tanned crust leather. Leather samples were pre-treated by cleaning with 70% v/v ethanol (5–10 mL per 10 cm² of leather). Figure 5 shows the pH and color fastness to rubbing of inks used on vegetable tanned leather.

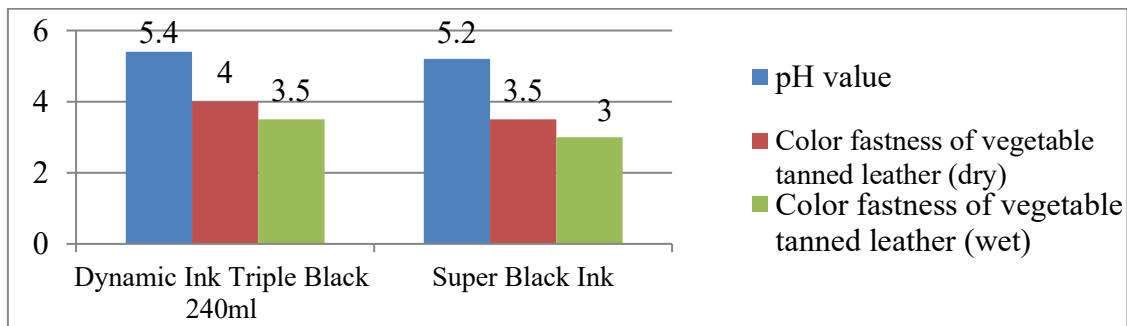


Figure 5. Ink Properties

Leather is a natural material made from animal hides, primarily composed of collagen fibers. The tanning process stabilizes the collagen fibers, making the leather durable and less prone to decomposition. Based on literature for this type of leather, it generally falls within a slightly acidic to neutral range (pH 4–6) [15]. Leather's sensitivity to pH is an important factor in determining the compatibility of tattoo inks. The pH of the inks used in this study was 5.4 for Dynamic Ink Triple Black 240ml and 5.2 for Super Black Ink, as measured using universal indicator strips. The pH of the leather itself was not measured;

literature [15, 16] reports that vegetable tanned crust leather typically exhibits a slightly acidic to neutral pH range (approximately 3.5–6.5). No previous studies have specifically investigated the compatibility of these commercially available tattoo inks with leather materials; therefore, this work represents one of the first systematic evaluations of their practical performance on vegetable tanned leather.

As shown in Figure 5, Dynamic Ink Triple Black 240ml generally showed better color fastness to rubbing than Super Black Inks on vegetable tanned cowhide crust leather. When choosing ink for tattooing leather, considering

the type of leather and the expected conditions of use is crucial. In Table 2 and 3, Dynamic Ink Triple Black 240ml generally offers better durability against rubbing, on vegetable-tanned leather, both dry and wet. Super black inks, while functional, showed less durability, particularly under wet conditions. The findings suggested that the Dynamic Ink Triple Black 240ml offers a reliable choice for enhancing the longevity and visual appeal of tattoos. The choice of Dynamic Ink Triple Black 240ml has already been described in Ink Selection section,

where its pH and performance were compared to Super Black Ink.

Planning an Experiment to Optimize Leather Tattoo Parameters

To achieve better results, Design-Expert version 13 software was used. Information on the factors and response function of the experiment is presented below (Tables 1 and 2). The color fastness values on leather to rubbing (Table 2) correspond to the results of the ink color fastness tests (Figure 5).

Table 1: Mathematical model factors for assessing the impact of tattooing

Factors	Factor levels		
	-1	0	+1
Cleaning alcohol concentration (A), milliliter per 10 cm ² leather	5	7.5	10
Needle speed (B), cycles/second	14	15	16
Number of coatings (C), units	1	2	3

Table 2: Experiment planning matrix and actual run number

No	Optimization factors			Optimization parameter		Actual run number
	A	B	C	Color fastness to rubbing, gray scale		
				Dry	Wet	
1	7.5	15	2	4.5	3.5	14
2	10	15	1	3	2.5	6
3	7.5	16	1	4	2.5	10
4	7.5	14	1	3.5	3	9
5	5	15	3	4	3	7
6	7.5	15	2	4.5	3.5	16
7	7.5	15	2	4.5	3.5	13
8	7.5	15	2	4.5	3.5	15
9	7.5	15	2	4.5	3.5	17
10	10	14	2	3.5	3	2
11	5	16	2	4.5	3	3
12	5	15	1	4	3	5
13	7.5	14	3	4.5	3	11
14	10	16	2	3	3	4
15	7.5	16	3	3.5	3	12
16	5	14	2	4.5	3.5	1
17	10	15	3	3.5	3	8

Table 3: Response 1: Color fastness to rubbing (dry)

Source	Sum of Squares	Df (Degrees of freedom)	Mean Square	F-value	p-value	Significance
Model	5.12	9	0.5691	66.95	< 0.0001	significant
A-Cleaning alcohol concentration	2.00	1	2.00	235.29	< 0.0001	
B-Needle Speed	0.0613	1	0.0613	7.21	0.0313	
C-Number of coatings	0.2112	1	0.2112	24.85	0.0016	
AB	0.1225	1	0.1225	14.41	0.0067	
AC	0.1225	1	0.1225	14.41	0.0067	
BC	0.6400	1	0.6400	75.29	< 0.0001	
Residual	0.0595	7	0.0085			
Lack of Fit	0.0475	3	0.0158	5.28	0.0709	Not significant
Pure Error	0.0120	4	0.0030			
Cor Total	5.18	16				

P-values less than 0.0500 indicated model terms are significant. In this case, A, B, C, AB, AC, and BC are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

From the ANOVA analysis, the final reduced regression models were established

$$Cfd=4.46-0.5(A)-0.0875(B)+0.1625(C)-0.175(AB)+0.175(AC)-0.4(BC) \quad (1)$$

Based on the ANOVA analysis in (Table 3) and the 3D plot shown in Figure 6, significant interaction effects were observed among cleaning alcohol concentration, needle speed, and the number of finishing agent coats on color fastness to rubbing (dry). The findings suggest that reducing cleaning alcohol concentration while increasing the number of

finishing agent coats enhances color fastness to rubbing (dry). Conversely, increasing both needle speed and cleaning alcohol concentration tends to decrease color fastness. However, improving color fastness is possible by reducing needle speed and increasing the number of finishing agent coats.

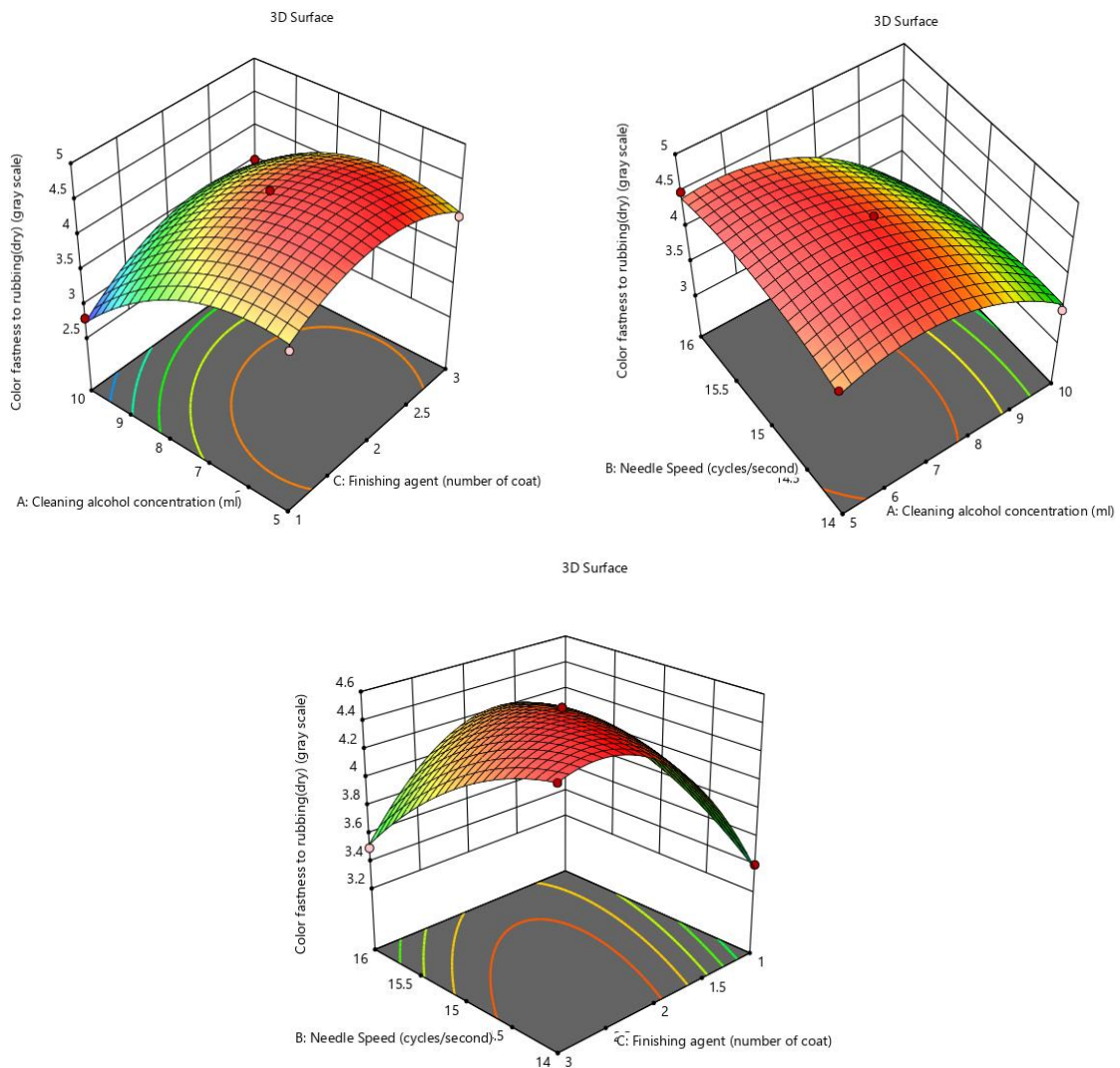


Figure 6. 3D plot graph of color fastness to rubbing (dry) to the other two factors

Table 4: Response 2: Color fastness to rubbing (wet)

Source	Sum of Squares	Df (Degrees of freedom)	Mean Square	F-value	p-value	Significance
Model	2.24	9	0.2487	51.78	< 0.0001	Significant
A-Cleaning alcohol concentration	0.2628	1	0.2628	54.71	0.0001	
B-Needle Speed	0.1128	1	0.1128	23.49	0.0019	
C-Number of coatings	0.2450	1	0.2450	51.00	0.0002	
AB	0.0156	1	0.0156	3.25	0.1143	
AC	0.1225	1	0.1225	25.50	0.0015	
BC	0.1225	1	0.1225	25.50	0.0015	
Residual	0.0336	7	0.0048			
Lack of Fit	0.0256	3	0.0085	4.27	0.0973	not significant
Pure Error	0.0080	4	0.0020			
Cor Total	2.27	16				

P-values less than 0.0500 indicate model terms are significant. In this case, A, B, C, AC, and BC are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those

required to support hierarchy), model reduction may improve the model. As illustrated in (Figure 7), there is a linear correlation between the predicted and experimental values, indicating that the regression model is well-suited for the data.

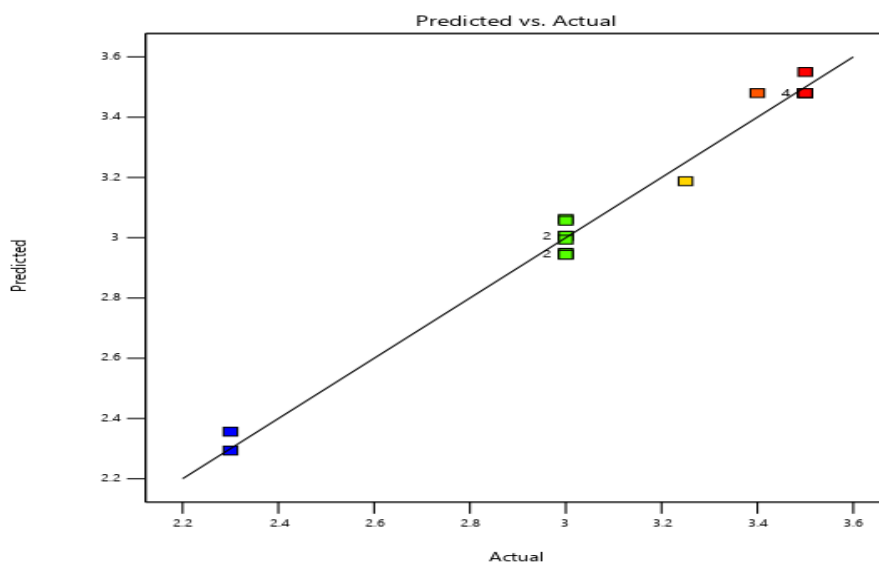


Figure 7. Color rub fastness (wet) predicted vs actual graph

According to the analysis of the ANOVA (Table 4), insignificant factors were removed to develop the final reduced regression models, as depicted in equation (2) using Coded factors. The regression equations demonstrate that cleaning alcohol concentration (A) and needle

speed (B) have a negative relationship with color fastness to rubbing (wet). Conversely, the number of coats of the finishing agent (C) shows a positive correlation with color fastness to rubbing (wet).

$$Cfw = 3.48 - 0.183(A) - 0.1188(B) + 0.1750(C) + 0.0625(AB) + 0.175(AC) + 0.175(BC) \quad (2)$$

Based on the ANOVA Table 3 and the 3D plots in Figure 8, significant interaction effects among cleaning alcohol concentration, needle speed, and the number of finishing agent coats

on color fastness to rubbing were observed. The plots indicated that increasing needle speed and cleaning alcohol concentration decrease color fastness to rubbing. Conversely,

increasing the number of finishing agent coats and decreasing cleaning alcohol concentration enhanced color fastness to rubbing (wet).

Similarly, increasing the number of finishing agent's coat, while decreasing needle speed also improves color fastness to rubbing (wet).

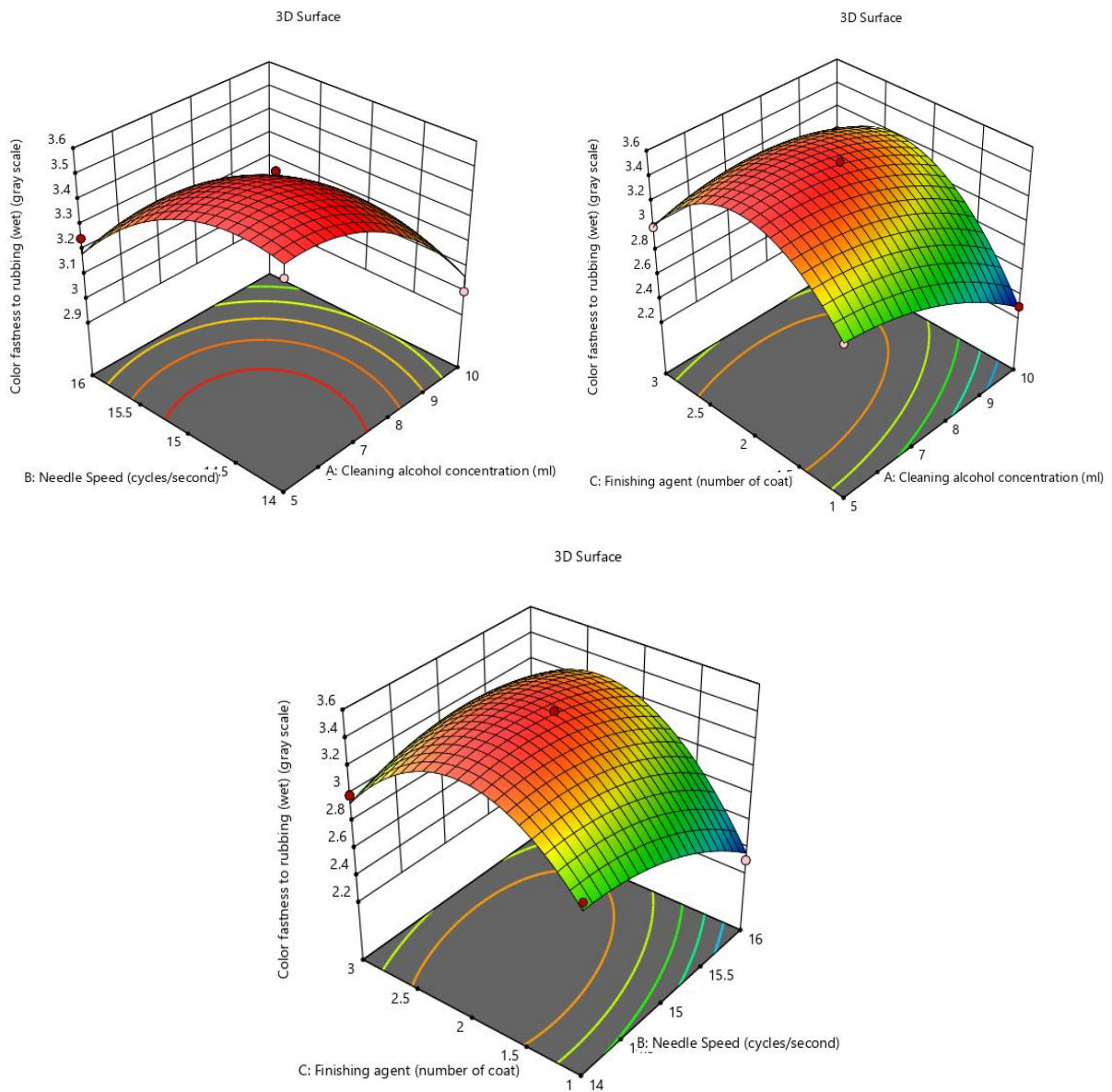


Figure 8. 3D plot graph of color fastness to rubbing (wet), to the other two factors

Optimal Conditions for Leather Tattooing

The Design-Expert (version 13) statistical software was employed to find the best compromise for the response variables. In this method, each response variable is represented using an individual desirability function that ranges from 0 to 1. The desirability function

assigns a value of 1 when the response variable achieves its target or goal, and it decreases towards 0 as the response variable moves away from the desired range. Table 5 illustrates how Design-Expert software determined the optimal conditions by setting goals and weighing the importance of both dependent and independent variables.

Table 5: The importance of leather tattooing process factors for color fastness to rubbing

Name	Goal	Lower Limit	Upper Limit	Importance
A: Cleaning alcohol concentration	is in range	5	10	3
B: Needle Speed	is in range	14	16	3
C: Number of coatings	is in range	1	3	3
Colorfastness to rubbing (dry)	maximize	3.5	4.5	3
Colorfastness to rubbing (wet)	maximize	2	3.5	3

Experimental Validation

The experiment aimed to evaluate the color fastness to rubbing, both in dry and wet conditions, of vegetable-tanned crust cowhide leather. The optimal values were 4.468 for dry conditions and 3.427 for wet conditions. In experimental run 5, the observed values were 4 for dry conditions and 3 for wet conditions. Based on pre-trial experiments and the analysis of color fastness to rubbing, the following optimal conditions were selected for subsequent experiments. Pre-treatment (ethanol volume): 10 mL per 10 cm² leather, Needle speed: 16 cycles/second and Number of finishing coats: 3 coats. This close correspondence between optimal and experimental values indicated that the leather's color fastness to dry rubbing was well within the expected range, with minor variations likely due to experimental factors. Similarly, the performance in wet conditions closely matched predictions, confirming the leather's consistent color fastness across different conditions.

The Effect of Tattooing on the Structure and Mechanical Properties of the Leather

Organoleptic Examination

The quality of tattoos on vegetable-tanned bovine crust leather was assessed using organoleptic examination, which includes both tactile and visual evaluation.

a) Visual Examination

Visual assessment revealed that the tattoo lines were clear and well-defined, with no visible bleeding or blurring at the edges. Ink distribution across solid areas was uniform, and shaded areas demonstrated smooth and gradual tonal transitions without abrupt color shifts. Fine details and intricate design

elements remained distinct, indicating controlled ink penetration and minimal lateral spread into adjacent leather areas.

b) Tactile Examination

Tactile examination determined that the slightly rough texture of vegetable-tanned leather before tattooing provides a good grip for tattooing tools, making it easier to control hand movements and apply consistent pressure. This texture helps the leather absorb ink more effectively, as the rough surface allows the ink to penetrate and adhere better, resulting in vibrant and lasting designs. However, after tattooing, vegetable tanned cowhide crust leather exhibits a moderate rough texture, but still it does not affect the leather properties, which had a slight effect.

Mechanical Properties

The original leather samples demonstrate a fairly high tensile strength (17.8 N/mm²), which is due to the action of mimosa tannins. Following tattooing, there was a slight decrease in tensile strength to 17.3 N/mm². This minor decline indicated that tattooing induces structural changes in the leather but does not significantly diminish its overall strength. Vegetable tanned crust leather, before tattooing, the elongation percentage was 28.40%, indicating a good degree of flexibility and the ability to stretch without breaking. After tattooing, the elongation percentage slightly decreases to 27.70%. This slight reduction suggested that the tattooing process has a minor effect on the leather's ability to stretch, making it slightly less flexible. The decrease in elongation from 28.40% to 27.70% suggested that tattooing has a minor impact on its flexibility. Vegetable tanned crust leather before tattooing; the tear strength was 25.0 N/mm. After tattooing, the tear strength was 24.7 N/mm. The tear strength indicated

the resistance of the leather to tearing. Vegetable-tanned crust leather has high tear strength, suggesting good resistance to tearing forces. There was a very slight decrease in tear strength. This minor reduction implied that tattooing has a negligible effect on the

leather's tear resistance. Vegetable-tanned crust leather maintains high tensile strength, reasonable flexibility, and strong tear resistance after tattooing. It is suitable for applications requiring durability and resistance to tearing.

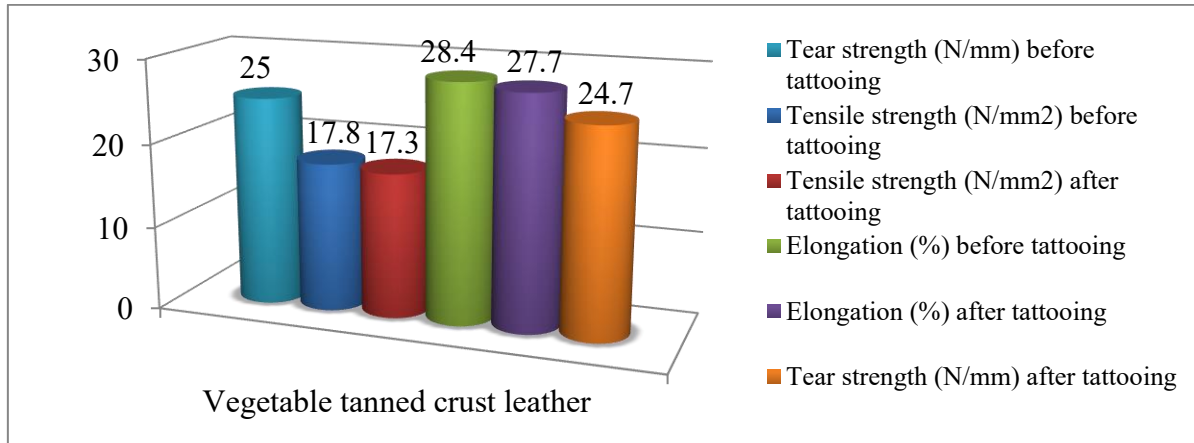


Figure 9. Mechanical properties of leather before and after tattooing

Abrasion Resistance

Abrasion resistance is a critical property of leather that measures its ability to resist surface wear caused by friction. Tattooing, a

process involving the insertion of dyes or inks into the leather through needle punctures, can affect the abrasion resistance of leather.

Table 6: Abrasion resistance of leather before and after tattooing

Leather Condition	Abrasion Damage	Standard Value (Scale)
Before Tattooing	No damage	0
After Tattooing	Slight damage	1

Table 6 offers information about the abrasion resistance of vegetable-tanned crust leather before and after tattooing. Vegetable-tanned crust leather before tattooing in dry conditions showed excellent abrasion resistance, with no damage observed even after 25,600 cycles. This indicated a high durability of the leather when dry. In wet conditions, the leather remains undamaged after 6,400 cycles, showing good wet abrasion resistance. After tattooing in dry conditions, the abrasion resistance decreases slightly as evidenced by slight damage after 25,600 cycles. This suggests that the tattooing process may weaken the leather's surface, making it more susceptible to abrasion. In wet conditions, slight damage is observed after 6,400 cycles, indicating that the weakening effect of tattooing is consistent in both dry and wet conditions. Despite this, the reduction in

abrasion resistance was relatively minor; indicating that the vegetable tanned crust leather of still maintains good durability even after tattooing.

Fourier Transform Infrared Spectroscopy

The Fourier Transform Infrared Spectroscopy (FTIR) spectra showed that tattooing vegetable-tanned crust leather with Dynamic Ink Triple Black 240ml resulted in the introduction of new chemical compounds and the possible modification of preexisting ones. The C-O bond is usually linked to the peak 1024 cm^{-1} . It revealed the presence of alcohols, ethers, or esters from the ink ingredients after tattooing. These might have originated from the ink's organic components or solvents. The C-O and O-H bonding can be associated with the peak 1217 cm^{-1} . It implies the existence of

phenolic or carboxylic acid derivatives from the ink or a reaction between the tannins in the leather and the ink in the setting of the tattooed leather. The peak of 1433 cm^{-1} is related to C-H bonding, particularly in $-\text{CH}_2-$ and $-\text{CH}_3$ groups. It suggested the presence of aliphatic chains, possibly from organic solvents or other components in the tattoo ink. The peak of 1538 cm^{-1} is characteristic of N-H and C-N bonding, typical of amides (Amide II band). The slight shift compared to the typical collagen peaks (1543 cm^{-1}) indicated some interaction or modification of the protein structure by the ink components.

The peak 1626 cm^{-1} corresponds to $\text{C}=\text{O}$ (Amide I band), and it is indicative of the carbonyl group in peptide bonds of proteins. The shift from 1645 cm^{-1} suggested modifications to the collagen structure, likely due to the interaction with ink components such as pigments or solvents.

The peak of 2919 cm^{-1} in the aliphatic $-\text{CH}_2-$ and $-\text{CH}_3$ groups is linked to C-H. It suggested that the tattoo ink had lengthy aliphatic chains, which may have come from fatty or organic ingredients. O-H is identified as

the peak at 3287 cm^{-1} , which is indicative of hydroxyl groups. This may be connected to the ink's phenolic hydroxyl groups, the residual water content, or collagen's hydrogen-bonded O-H groups that may have come into contact with the ink.

Following tattooing with Dynamic Ink Triple Black 240ml, the FTIR spectra of vegetable-tanned crust leather revealed new and altered peaks that were suggestive of the interaction between the ink components and the leather. The existence of ink solvents or reaction products was suggested by the addition of new or modified C-O and O-H ($1024, 1217\text{ cm}^{-1}$). An alteration to the collagen structure caused by the ink was suggested by changes in the amide regions ($1538, 1626\text{ cm}^{-1}$), hydroxyl groups (3287 cm^{-1}) from residual water, ink components, or changed collagen, as well as aliphatic chains ($1433, 2919\text{ cm}^{-1}$) from ink components. These peaks show the tattoo ink's assimilation and interaction with the leather, showing both the ink's physical deposition and possible chemical reactions with the organic matrix of the leather.

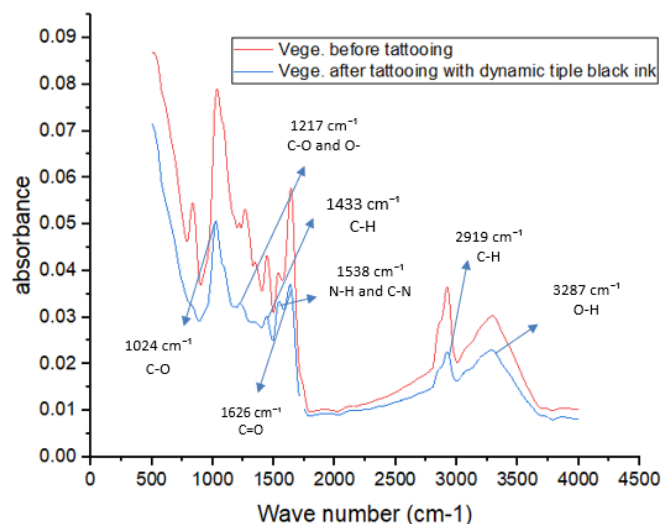


Figure 10. IR spectrograms of leather before and after tattooing

CONCLUSIONS

Leather embellishment, a rich art form, involves manipulating leather fibers to create precise designs and increase interest in leather products is significant due to their durability, versatility, and timeless appeal. Tattooing is a

form of body modification that consists of inserting tattoo ink, dyes, and pigments into the dermis layer of the skin, either permanently or temporarily. The study investigated the compatibility and effects of tattooing on cowhide vegetable-tanned crust leather, focusing on ink selection, application

techniques, and properties of the leather. The study concluded that Dynamic Ink Triple Black 240ml is a reliable choice for tattooing such leather due to its superior color fastness to rubbing and compatibility with leather's natural pH. The optimized tattooing process and ink selection resulted in minimal changes to the leather's mechanical properties, ensuring its suitability for applications requiring durability and resistance to tearing. Fourier Transform Infrared Spectroscopy (FTIR) analysis confirmed the interaction between ink components and leather, demonstrating the ink's effective assimilation and chemical reactions with the leather matrix. Despite a slight decrease in abrasion resistance, strength and elongation, cowhide vegetable-tanned crust leather maintains its overall strength and durability after tattooing, making it a viable material for artistic and functional applications.

Data Availability

The data collected and analysed during this study are included in the paper and can also be accessed through a reasonable request addressed to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Megabi Adane Yizengaw wrote the original draft and designed the study, performed the experiments, analyzed the data, and contributed materials/analysis tools. Megabi Adane Yizengaw revised the methodology, critical supervision of manuscript for academic content, and finally, Tamrat Tesfaye gave final approval for the version to be published.

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REFERENCES

1. Tsega, T.T., Thoben, K.D., Rao, D.K.N., Haile, B., Leather and Textile Industries - Strategic Sectors for Ethiopia to Gain Capability of Manufacturing for Global Market Competitiveness: A Literature Review, *Ethiop J Sci Technol*, **2022**, <https://doi.org/10.4314/ejst.v15i1.2>.
2. Anonymous, Grand View Research Publishes Report on Automotive Plastics Market, *Addit Polym*, **2023**, [https://doi.org/10.12968/S0306-3747\(23\)70132-2](https://doi.org/10.12968/S0306-3747(23)70132-2).
3. Cafasso, A.M., From Hide to Handbag: A Holistic Review of the Leather Industry and Its Environmental Impact, *GLO 100 Introduction to Global Studies: Policy Analysis Papers*, **2023**, available from <https://digitalcommons.salve.edu/glo100/3>.
4. Tirpude, R., Study of Impact of Digital Marketing on Consumer Buying Behaviour for Electronic Goods, *Int J Res Appl Sci Eng Technol*, **2022**, 10, 2, 905-909, <https://doi.org/10.22214/ijraset.2022.40348>.
5. Shautrina, A., Pengolahan Kulit Sintetis Sebagai Embellishment Pada Busana Demi Couture, **2020**, available from: <https://repositori.telkomuniversity.ac.id/home/catalog/id/161412/slug/pengolahan-kulit-sintetis-sebagai-embellishment-pada-busana-demi-couture.html>.
6. El-Fanagely, B.R., The Role of Laser Cutting Technology in Enriching Aesthetic Values and Highlighting Artistic Formulas on Leather Fabrics, *Int Des J*, **2022**, 12, 5, 165-177, <https://doi.org/10.21608/idj.2022.260580>.
7. Moktadir, M.A., Sarker, Md.R., Sharif, T., Abedin, M.Z., A Decision Support Model to Investigate the Pandemic Recovery Challenges and Strategies in the Leather Supply Chain, *Ann Oper Res*, **2023**, <https://doi.org/10.1007/s10479-023-05708-5>.
8. Thompson, B.Y., 2. "I Want to Be Covered", in B.Y. Thompson (ed.), *Covered in Ink. Tattoos, Women and the Politics of the Body*, **2015**, New York University Press, p. 35-64, <https://doi.org/10.18574/nyu/9780814760000.003.0003>.
9. Ahmed, M.D., Maraz, K.M., Khan, R.A., Prospects and Challenges of Chrome Tanning: Approach a Greener Technology in Leather Industry, *Scientific Review*, **2021**, 7, 3, <https://doi.org/10.32861/sr.73.42.49>.
10. Cirillo, C., Iuliano, M., Florio, C., Fierro, F., Gallucci, L., Maffei, G., Loi, A., Scarpa, D., Sarno,

- M., High Performance Leathers Finishing through Zero Waste and Metal-free Leather Wastes Valorization, *Sci Rep*, **2025**, 15, 1, 18105, <https://doi.org/10.1038/s41598-025-03182-6>.
11. Guida, L., Romani, A., Negri, D., Cavallaro, M., Levi, M., 3D-printable PVA-based Inks Filled with Leather Particle Scraps for UV-assisted Direct Ink Writing: Characterization and Printability, *Sustain Mater Technol*, **2025**, 44, e01335, <https://doi.org/10.1016/j.susmat.2025.e01335>.
 12. Becker, S.J., Cassisi, J.E., Applications of Medical Tattooing: A Systematic Review of Patient Satisfaction Outcomes and Emerging Trends, *Aesthet Surg J Open Forum*, **2021**, 3, 3, <https://doi.org/10.1093/asjof/ojab015>.
 13. Reddersen, K., Gregersen, D.M., Tittelbach, J., Wiegand, C., Tattooed Human *in vitro* Skin Model for Testing the Biocompatibility of Tattoo Inks and Healing Progression after Tattooing, *Sci Rep*, **2025**, 15, 1, 2277, <https://doi.org/10.1038/s41598-025-86813-2>.
 14. Zhang, L., Jiang, M., Chen, Z., Zhang, X., An, W., Wang, S., Zhao, J., A Novel Polymer Platform for Endoscopic Tattooing with High Efficacy and Safety, *Front Bioeng Biotechnol*, **2024**, 12, 1409681, <https://doi.org/10.3389/fbioe.2024.1409681>.
 15. Teklemedhin, T.B., Gebretsadik, T.T., Gebrehiwet, T.B., Gebrekidan, G.A., Edris, M., Teklegiorgis, N.T., Hagos, K.B., Vegetable Tannins as Chrome-Free Leather Tanning, *Adv Mater Sci Eng*, **2023**, 2023, 1, 6220778, <https://doi.org/10.1155/2023/6220778>.
 16. Covington, A.D., Wise, W.R., Tanning Chemistry: The Science of Leather, **2019**, Royal Society of Chemistry, <https://doi.org/10.1039/9781839168826>.

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