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	CONTENTS	***CUPRINS***	***SOMMAIRE***	
Ulbosin ESHBAEVA JAMALOVNA **Gökhan ZENGIN** **Bahri BAŞARAN** **Nargiza ALIYEVA BAXTIKHOZIYEVNA**	Obtaining Collagen Hydrolyzates from Secondary Products of Chrome-Tanned Leather	Obținerea hidrolizatelor de colagen din produse secundare ale pielii tăbăcite în crom	Obtention d'hydrolysats de collagène à partir de sous-produits du cuir tanné au chrome	**3**
Megabi Adane YIZENGAW **Tamrat TESFAYE**	Tattoo as a Way of Finishing Vegetable-Tanned Crust Leather	Tatuajul ca modalitate de finisare a pielii crust tăbăcite vegetal	Le tatouage comme technique de finition pour la croûte de cuir au tannage végétal	**11**
WIJAYANTI **Elis NURBALIA** **Wahyu Fajar WINATA** **Prasetyo HERMAWAN**	Synthesis of Chitosan Beads/Active Charcoal as Adsorbent of Yellow Acid 25 and Acid Red 73	Sinteza perlelor de chitosan/cărbune activ ca adsorbant pentru coloranții Acid Yellow 25 și Acid Red 73	La synthèse de billes de chitosane/charbon actif comme adsorbant pour les colorants Acid Yellow 25 et Acid Red 73	**27**
Arun Kumar GAIKWAD **Adity SAXENA**	Challenges in Protective Footwear for India's Disaster Management Workforce: A Design Thinking Approach	Provocări legate de încălțămintea de protecție pentru personalul de gestionare a catastrofelor din India: o abordare bazată pe design thinking	Les défis liés aux chaussures de protection pour le personnel chargé de la gestion des catastrophes en Inde : une approche basée sur le design thinking	**37**
	European Research Area	Spaţiul european al cercetării	Espace Européen de la Recherche	**51**

OBTAINING COLLAGEN HYDROLYZATES FROM SECONDARY PRODUCTS OF CHROME-TANNED LEATHER

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OBTAINING COLLAGEN HYDROLYZATES FROM SECONDARY PRODUCTS OF CHROME-TANNED LEATHER

ABSTRACT. In many tanneries, chrome-tanned leather shavings are still viewed as waste, despite their high collagen content and potential for reuse. This study focused on developing a process to extract collagen hydrolysates from these shavings using alkaline hydrolysis. The lab work involved several phases of testing with NaOH, KOH, and $Ca(OH)_2$ under different concentrations and temperatures, followed by further purification using barium chloride. The results of the study showed that chromium levels dropped dramatically, and the collagen that remained had strong adhesive properties, measured using standard surface tension and contact angle methods. Early experiments showed swelling issues and filtration delays, which the researchers had to troubleshoot by adjusting hydrolysis time and alkali ratios. But by the final stage, the method proved reliable. The broader takeaway here is that collagen recovery from chrome waste could not be just chemically viable—it could also offer real industrial and environmental value if adopted more widely.
KEYWORDS: adhesive properties, alkaline hydrolysis, chrome-tanned leather, collagen hydrolysates, waste recycling

OBȚINEREA HIDROLIZATELOR DE COLAGEN DIN PRODUSE SECUNDARE ALE PIELII TĂBĂCITE ÎN CROM

REZUMAT. În multe tăbăcării, răzătura de piele tăbăcită în crom este considerată deșeu, în ciuda conținutului ridicat de colagen și a potențialului de reutilizare. Acest studiu s-a concentrat pe dezvoltarea unui proces de extragere a hidrolizatelor de colagen din aceste răzături folosind hidroliza alcalină. Lucrările de laborator au implicat mai multe faze de testare cu NaOH, KOH și $Ca(OH)_2$ la diferite concentrații și temperaturi, urmate de o purificare ulterioară folosind clorură de bariu. Rezultatele studiului au arătat că nivelurile de crom au scăzut dramatic, iar colagenul rămas a avut proprietăți adezive puternice, măsurate folosind metode standard precum tensiunea superficială și unghiul de contact. Experimentele timpurii au indicat probleme legate de gonflare și întârzieri la filtrare, pe care cercetătorii au trebuit să le rezolve prin ajustarea timpului de hidroliză și a raporturilor alcaline. Dar, până în etapa finală, metoda s-a dovedit fiabilă. Concluzia generală este că recuperarea colagenului din deșeurile de piele tăbăcită în crom nu ar putea fi doar viabilă din punct de vedere chimic – ar putea oferi, de asemenea, o valoare industrială și de mediu reală dacă este adoptată pe scară mai largă.
CUVINTE CHEIE: proprietăți adezive, hidroliză alcalină, piele tăbăcită în crom, hidrolizate de colagen, reciclarea deșeurilor

OBTENTION D'HYDROLYSATS DE COLLAGÈNE À PARTIR DE SOUS-PRODUITS DU CUIR TANNÉ AU CHROME

RÉSUMÉ. Dans de nombreuses tanneries, les copeaux de cuir tanné au chrome sont encore considérés comme des déchets, malgré leur teneur élevée en collagène et leur potentiel de réutilisation. Cette étude s'est concentrée sur le développement d'un procédé d'extraction d'hydrolysats de collagène à partir de ces copeaux par hydrolyse alcaline. Les travaux en laboratoire ont comporté plusieurs phases de tests avec NaOH, KOH et $Ca(OH)_2$ à différentes concentrations et températures, suivies d'une purification supplémentaire au chlorure de baryum. Les résultats ont montré une diminution drastique de la teneur en chrome et de fortes propriétés adhésives du collagène restant, mesurées par les méthodes classiques de tension superficielle et d'angle de contact. Les premières expériences ont révélé des problèmes de gonflement et des retards de filtration, que les chercheurs ont dû résoudre en ajustant la durée d'hydrolyse et les proportions d'alcali. Finalement, la méthode s'est avérée fiable. L'enseignement principal est que la récupération du collagène à partir des déchets de cuir tanné au chrome pourrait non seulement être chimiquement viable, mais aussi présenter un réel intérêt industriel et environnemental si elle était plus largement adoptée.
MOTS-CLÉS : propriétés adhésives, hydrolyse alcaline, cuir tanné au chrome, hydrolysats de collagène, recyclage des déchets

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INTRODUCTION

The issue of rational waste utilization remains one of the most pressing global challenges. On the one hand, waste is a significant source of environmental pollution; on the other hand, it serves as a raw material for valuable products through recycling processes. For example, in the leather industry, waste generated during production and processing—as well as by-products from secondary manufacturing processes—can be considered recyclable raw materials [1].

Leather industry waste can be classified into chrome-free and chrome-containing leather waste, depending on the presence of chromium. The most hazardous type of waste pollutants are chrome-containing wastes. Chrome leather shavings typically contain about 90% collagen and 2–4% chromium [2]. Therefore, the efficient recycling of such waste is crucial for the sustainable development of the leather industry and can bring significant economic benefits. The most effective method for processing chrome leather shavings involves separating collagen and chromium, which can be done using high-level and low-level hydrolysis techniques [3].

Chrome leather shavings are generated during the leveling of leather surfaces. In the leather processing stage, uneven parts of the hide (such as the tail sections or parts of the head that are unsuitable for production) are removed. During the leveling of thick hides, up to 10% chrome leather shavings are produced. These shavings typically have an average width of about 10 mm, a length not exceeding 120–150 mm, and a thickness ranging from 0.5 to 1 mm. Chrome leather shavings fall under the category of secondary raw material waste from leather production [4].

Currently, unused portions of these shavings are often dumped in open areas near leather processing facilities, posing serious environmental risks [5]. Waste containing chromium can cause respiratory problems and a decreased ability to fight various diseases [6]. Moreover, the incineration of such waste contributes to severe air pollution due to the release of toxic hexavalent chromium (Cr+6), halogenated organic compounds, aromatic hydrocarbons, and other pollutants [7].

This study aims to extract collagen hydrolysate from secondary chrome-containing waste in the leather industry, minimize the volume of waste, implement an environmentally safe processing method, and follow the principles of “green technology”—representing an innovative and sustainable approach in this field.

EXPERIMENTAL

Alkaline Hydrolysis Process

During the recycling of chrome leather shavings, approximately 60–75% of collagen (Cr_2O_3) remains bound within the chrome-containing waste. The separation and removal of the chromium element from chrome leather shavings—known as dechromation—are carried out through a hydrolysis process under both alkaline and acidic conditions. Alkaline hydrolysis enables the removal of chromium from solid leather waste without damaging the collagen matrix.

The high efficiency of chromium removal depends on three key factors: firstly, alkaline treatment effectively breaks the bonds between chromium and collagen, forming a precipitate of $Cr(OH)_3$. Secondly, acid treatment dissolves the $Cr(OH)_3$ precipitate, thereby partially separating chromium from collagen. Thirdly, the complete separation of chromium and collagen can ultimately be achieved through sequential or combined treatments.

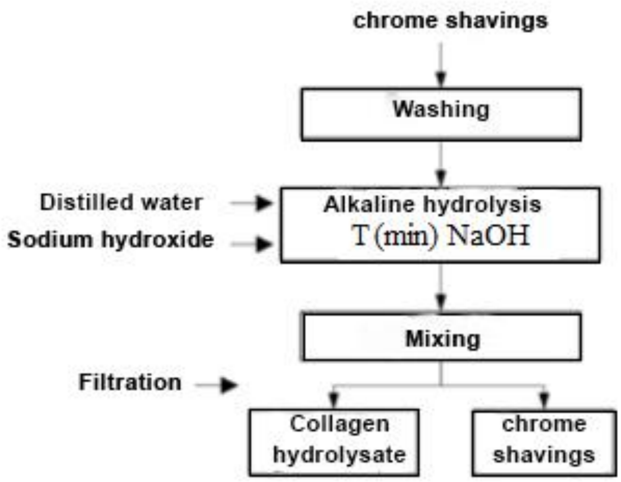


Figure 1. Alkaline hydrolysis process

A major drawback of the hydroxide-based method is that when acid is added to dissolve the $Cr(OH)_3$ precipitate, the collagen fibers—having lost their stabilizing chromium component—swell significantly. These swollen collagen fibers may restrict water release from the leather during filtration under pressure, thereby reducing process efficiency [8].

When peptide bonds in proteins are broken, the molecular chains are cleaved into two parts. Continued processing results in increasingly smaller fragments, making their removal easier. This progression not only facilitates more efficient chromium removal but also preserves the structural integrity of the leather [4].

The hydrolysis reaction of collagen proceeds as follows:

$$P\text{-}(CH_2)_nCONH_2 + H_2O + OH^- \rightarrow P\text{-}(CH_2)_nCO^-_2 + NH_3 \quad (1)$$

The chemical reaction for the chromium extraction process is usually as follows:

$$Cr_2(SO_4)_3 + 6NaOH = 2Cr(OH)_3\downarrow + 3Na_2SO_4 \quad (2)$$

During the treatment of chrome shavings with alkaline solutions, OH^- ions displace the carboxyl groups in the collagen ion chains that are coordinated with Cr(III), leading to the formation of a $Cr(OH)_3$ precipitate and the release of Cr(III) from the collagen fibers. However, separating $Cr(OH)_3$ from the collagen fibers remains a challenging task, as it requires the addition of acid to dissolve and remove the precipitate. Preventing the re-binding of dissolved Cr(III) and avoiding excessive hydrolysis of the collagen fibers are critical factors for achieving an efficient and complete separation of Cr(III) from the collagen matrix.

The following reactions occur under alkaline conditions:

$$2Cr_2O_3 + 8OH^- + 3O_2 = 4CrO_4^{2-} + 4H_2O \text{ in alkaline media;} \quad (3)$$

$$2Cr_2O_3 + 2H_2O + 3O_2 = 2Cr_2O_7^{2-} + 4H^+ \text{ in basic (alkaline) environment with water} \quad (4)$$

To address these issues, treatment with a solution of uniform concentration (NaOH, pH 13.5, 30 °C, for 3 hours, and 5% Na_2SO_4) facilitates the formation of the chromium precipitate $Cr(OH)_3(H_2PO_4)_2^-$ through the hydrolysis of collagen fibers. The behavior of chromium (III) under these conditions aligns with the reactions mentioned above [5].

Recycling chrome shavings significantly contributes to reducing pollution from the leather industry, while enabling the production of high-value functional materials. It has been scientifically proven that collagen hydrolysate is an excellent adhesive, and chrome leather waste contains up to 17% adhesive content. Hydrolyzing chrome-containing leather waste not only enables the separation of chromium but also supports its application in product manufacturing—one of today's most pressing environmental and industrial challenges.

Materials and Methods

Process for Obtaining Collagen Hydrolysates from Chrome Leather Waste

To extract collagen hydrolysates from chrome-containing leather waste, samples were collected from the "Yuksalish Charm Sanoat" LLC enterprise in the Namangan region and transported to the scientific laboratory of the "Chemical Technology" Department at the Namangan Institute of Engineering and Technology. Before beginning the experiments, the chromium content and overall composition of the chrome leather waste were analyzed under ISO 5398-1 standards. These tests were carried out using the EDX-7200 laboratory analyzer, and the results are presented in Table 1.

Table 1: The amount of Cr element in the process after hydrolysis

	Elements	Share (%)
1	Cr	53.533
2	Cl	29.524
3	S	12.665
4	Si	0.968
5	Ca	0.721
6	Fe	2.257
7	K	0.128
8	Zn	0.007

Based on the data obtained, it was found that the combined content of chromium (Cr) and chlorine (Cl) accounted for approximately 54%, significantly higher than other detected elements. To isolate chromium from the leather shavings, the alkaline hydrolysis method was applied. For this method, key reagents such as sodium hydroxide (NaOH), potassium hydroxide (KOH), and calcium hydroxide ($Ca(OH)_2$) were used.

Hydroxide solutions were prepared at various concentrations, taking into account key parameters such as temperature and hydrolysis duration. These were then applied to selected ratios of chrome leather waste (based on dry mass), with a total reaction volume of 1 liter. The use of these alkaline agents facilitates the separation of chromium from the collagen matrix, precipitating it as chromium hydroxide [3].

After precipitation, the chromium hydroxide was dissolved using acid solutions and subsequently removed as a soluble salt via filtration [5].

In the first stage of hydrolysis, solutions of sodium hydroxide (NaOH), potassium hydroxide (KOH), and calcium hydroxide ($Ca(OH)_2$) were used. The alkali loosens the collagen fibers, converting them into soluble peptides. For each 100 g sample, a 1:1.5 ratio of 5% KOH solution was heated at 70 °C for 20–60 minutes. Under the influence of temperature and the addition of chromium (Cr) with alkali (NaOH or KOH), a green precipitate—chromium(III) hydroxide ($Cr(OH)_3$)—was formed:

$$Cr^{3+} + 3OH^{-} \rightarrow Cr(OH)_3 \quad (5)$$

When additional alkali was added to the chromium(III) hydroxide, the precipitate dissolved in the solution, and the green color disappeared, leaving the solution colorless. After the leather shavings were fully absorbed into the reaction, 3% NaOH was added, and continuous stirring was performed throughout the hydrolysis process. The results are presented in Table 2.

Table 2: The amount of Cr element in the process after hydrolysis

	Elements	Share (%)
1	K	0.294
2	Cr	0.235
3	S	0.054
4	Si	0.235
5	Ca	0.030
6	Fe	0.004
7	Cl	0.029
8	H_2O	99.116

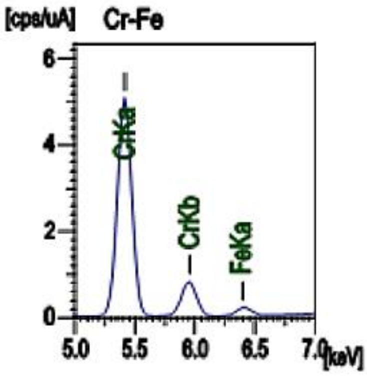


Figure 2. Results of X-ray spectral analysis of Cr and Fe elements

From the table, it is evident that after alkaline hydrolysis, the Cr content in chrome-containing leather waste decreased to 0.235%, indicating significant removal of chromium. After hydrolysis, the collagen hydrolysate was filtered and separated from the alkaline-treated chrome leather waste. The hydrolysate was stored in a measuring flask at 4 °C. Following the hydrolysis, the remaining Cr content in the chrome leather waste was re-analyzed using the EDX-7200 laboratory device (see Table 3).

Table 3: The amount of Cr in the filtered collagen hydrolysate

	Elements	Share (%)
1	K	0.282%
2	Cr	0.005%
3	S	0.102%
4	Si	0.248%
5	Cl	0.069%
6	Fe	0.000%
7	Zn	0.001%
8	H_2O	99.289%

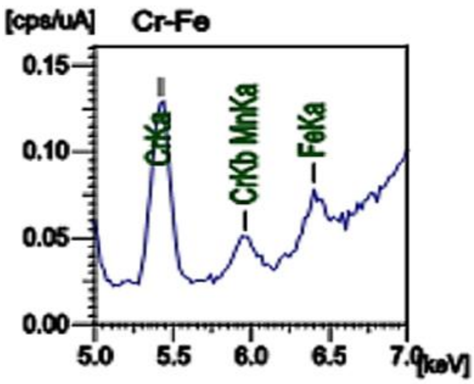


Figure 3. Results of X-ray spectral analysis of Cr and Fe elements

The filtered collagen hydrolysate was found to contain only 0.005% Cr, showing effective reduction. To completely remove Cr ions from the hydrolysate, a 5% $BaCl_2$ solution was added. As a result, a white precipitate of barium chromate ($BaCrO_4$) was formed:

$$Cr^{3+} + Ba^{2+} \rightarrow BaCrO_4\ (s) \qquad (6)$$

This reaction was used to detect the presence of chromium ions, as barium chromate is white and has very low solubility. The precipitate was then removed by filtration. To determine the final Cr content in the filtered collagen hydrolysate, a third-phase analysis was conducted, and the results are shown in Table 4.

Table 4: The amount of Cr element in the process after Ba hydrolysis

	Elements	Share (%)
1	Ba	2.175%
2	Cl	1.839%
3	S	0.016%
4	Si	0.237%
5	K	0.071%
6	Fe	0.000%
7	Zn	0.000%
8	H_2O	95.550%

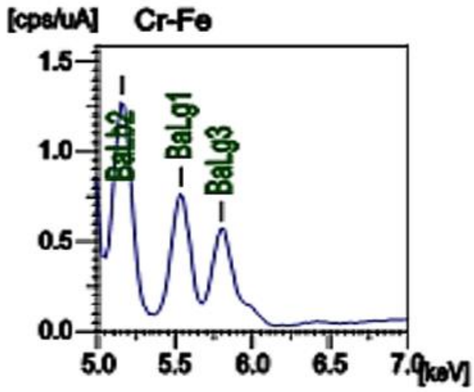


Figure 4. Results of X-ray spectral analysis of Cr and Fe elements

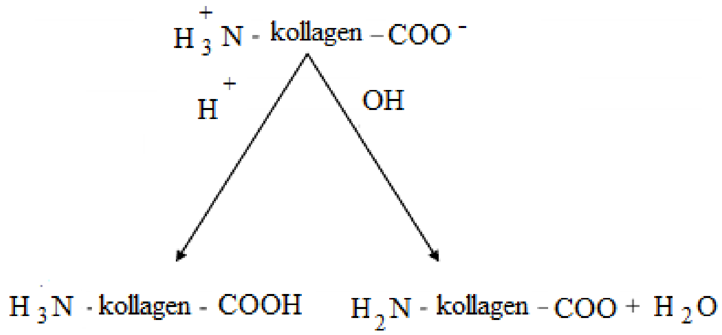
RESULTS AND DISCUSSIONS

Collagen Hydrolysate and Its Adhesive Properties

Analysis results confirmed that the collagen hydrolysates were completely purified from chromium. During alkaline hydrolysis, chromium(III) ions reacted with hydroxide ions, forming a $Cr(OH)_3$ precipitate, while collagen was hydrolyzed. The effects of typical variables in the alkaline hydrolysis method—such as reaction time, alkali concentration (%), and temperature (°C)—on the degree of hydrolysis, total protein content, and its efficiency (%) were studied.

To this end, an optimization study was carried out using statistical experimental models, and all obtained values were controlled under ISO 5398-1 standards.

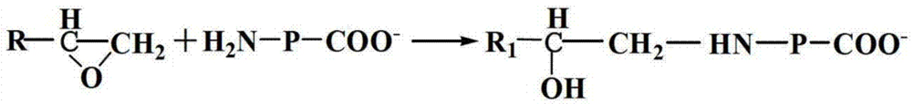
Based on the experiments conducted, the interaction of acid and alkaline agents with chrome-containing leather waste can be represented using the following conceptual process:



(7)

The main factors influencing the efficiency of collagen protein extraction from chrome leather waste include: type of alkali, amount of alkali used, primary hydrolysis temperature, water consumption, enzyme release and exposure time, and others.

From the above, it can be concluded that the method of recycling chromium shavings produced during the leather leveling process is characterized as a technical process for extracting collagen protein, consisting of the following stages: Leather shavings → pre-treatment → primary hydrolysis → mixing → filtration of the solution → collagen hydrolyzes → amino acids and polypeptides are produced, and chromium precipitates. In the targeted alkaline hydrolysis method, the reaction for obtaining water-soluble collagen hydrolysate is as follows:



(8)

H2N – COO- structural formula of collagen hydrolysate:

$$-\!\!\left[NH\text{-}CO\right]_n\!\!- \;;$$

(9)

In preliminary studies of alkaline hydrolysis, reaction time and NaOH concentration were identified as the key variables controlling the process. Using this method, collagen hydrolysate was successfully extracted from chrome-containing leather waste. The product obtained through high-temperature heating of collagen was referred to as “glue.”

The adhesive properties—Wa (work of adhesion), Y (surface tension), and the equilibrium contact angle—were calculated according to GOST 10028-81 [9]. Contact angles were measured on glass slides using 5% collagen hydrolysate under a horizontal microscope. After introducing a droplet onto the gel surface and waiting 3 minutes, the measured angle was recorded as the equilibrium contact angle. Measurement accuracy was ±2°.

Table 5: Adhesion properties of collagen hydrolysates in different technological variants

Options	Temperature ºC	Adhesion, N/m	Mass fraction, %
Process 1: Hydrolysis with NaOH	50	1598	0.20
Process 2: Hydrolysis with NaOH	70	1619	0.21
Process 3: Hydrolysis with NaOH	90	1658	0.22
Control	70	1588	0.28
According to GOST-325280	70	at least 1570	At most 0.3

The resulting collagen hydrolysate was water-soluble, and when heated above 90 °C, it formed a thicker, jelly-like gel. After heating, the hydrolysate was collected and its adhesive properties were studied. The results are summarized in Table 5.

As shown in the table, under hydrolysis conditions using NaOH at 90 °C, the collagen hydrolysate exhibited the highest adhesive strength of 1658 N/m. Across all experimental samples, the collagen hydrolysates obtained from chrome leather waste showed high adhesive performance. The final product was odorless, with a structure resembling sticky, adhesive gel.

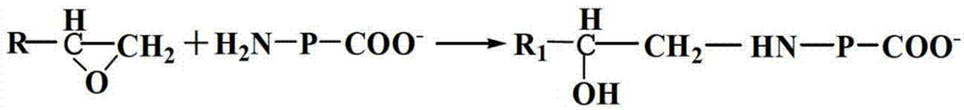
Additionally, the third experimental process demonstrated approximately 37% efficiency, which was higher compared to the first and second trials. The pH level of the collagen hydrolysates was found to be in the 7–8 range, indicating a neutral to mildly alkaline nature.

CONCLUSIONS

During the process of obtaining collagen hydrolysates from chrome-containing leather waste, the content of chromium (Cr) and the total amount of other elements present in the waste were analyzed using the EDX-7200 laboratory analyzer. In alkaline hydrolysis, chromium(III) ions react with hydroxide ions, resulting in the formation of trivalent chromium hydroxide precipitate ($Cr(OH)_3$), while the collagen undergoes hydrolysis.

The influence of key variables specific to the alkaline hydrolysis method—such as reaction time, alkali concentration (%), and temperature (°C)—was evaluated in terms of hydrolysis efficiency, total protein yield, and process effectiveness (%). Among them, reaction time and sodium hydroxide concentration were identified as critical parameters for process optimization.

As a result of the experiment, chromium present in the chrome shavings was successfully separated, and collagen hydrolysate was obtained.



(10)

Notably, under hydrolysis conditions using NaOH at 90 °C, the resulting collagen hydrolysate exhibited a high adhesive strength of 1658 N/m, indicating excellent adhesive properties.

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TATTOO AS A WAY OF FINISHING VEGETABLE-TANNED CRUST LEATHER

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TATTOO AS A WAY OF FINISHING VEGETABLE-TANNED CRUST LEATHER

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 tatuate 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 (C_2H_5OH) 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.

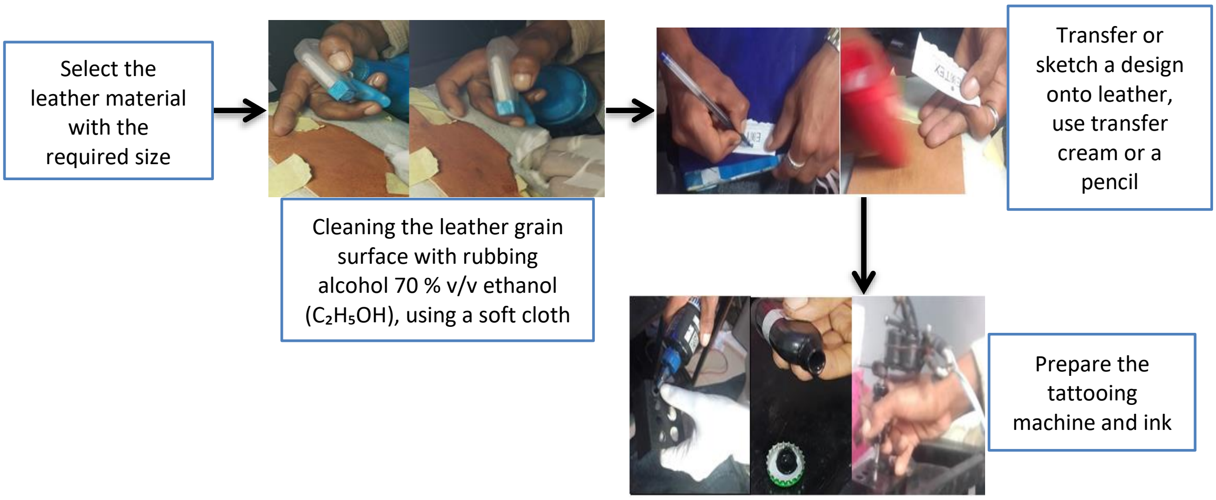

Figure 1. Material preparation

Tattooing Process

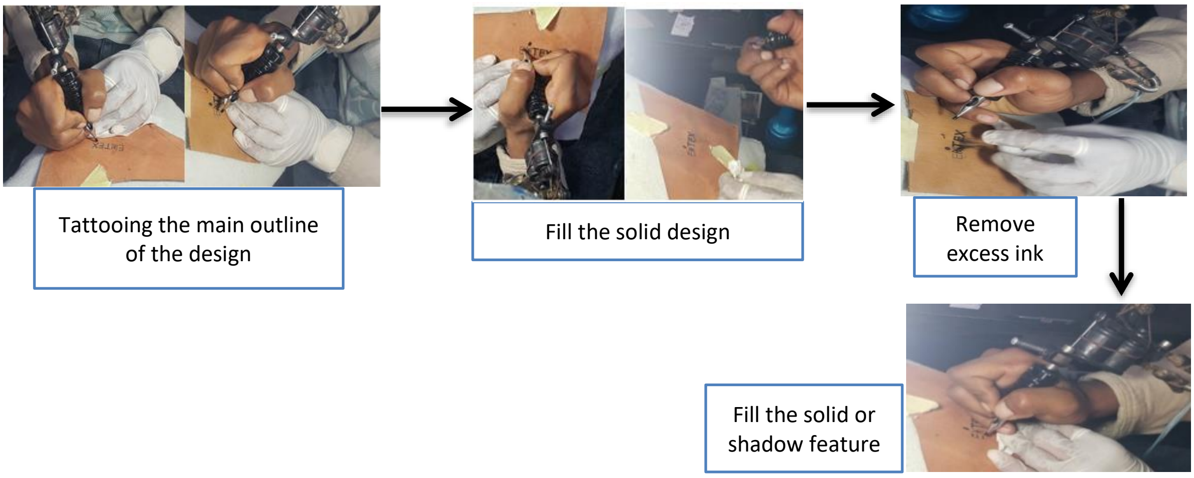

Figure 2. Tattooing process steps

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 (C_2H_5OH), 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.

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.

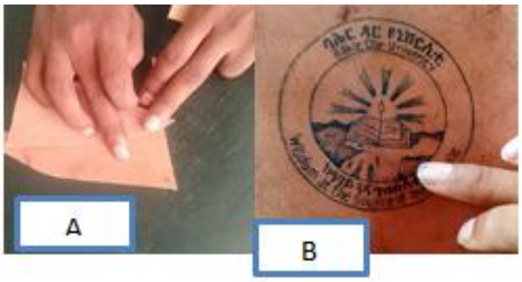

Figure 4. Tactile examination of leather before tattooing (A) and after tattooing (B)

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.

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.

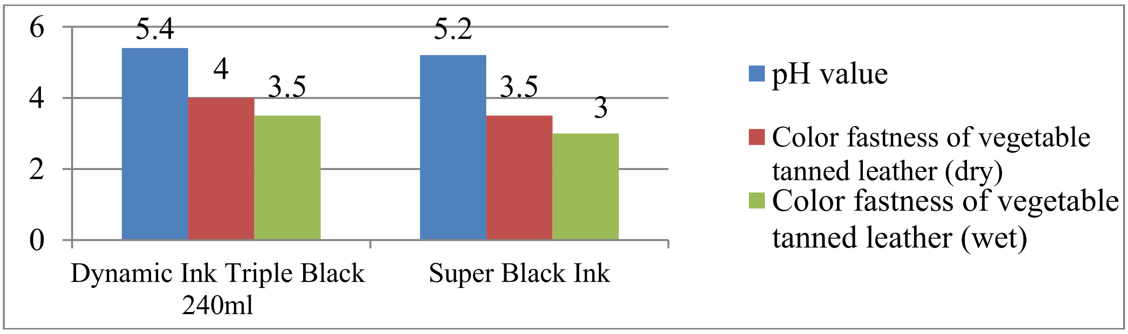

Figure 5. Ink Properties

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 cm² 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 Color fastness to rubbing, gray scale		Actual run number
	A	B	C	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 after eliminating insignificant factors, as demonstrated by the following regression equations in terms of coded factors, shown in equation (1). The regression equations reveal that the cleaning alcohol concentration (A) and needle speed (B) negatively correlate with the color fastness to rubbing (dry). In contrast, the number of coats of the finishing agent (C) has a positive correlation with the color fastness to rubbing (dry).

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

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.

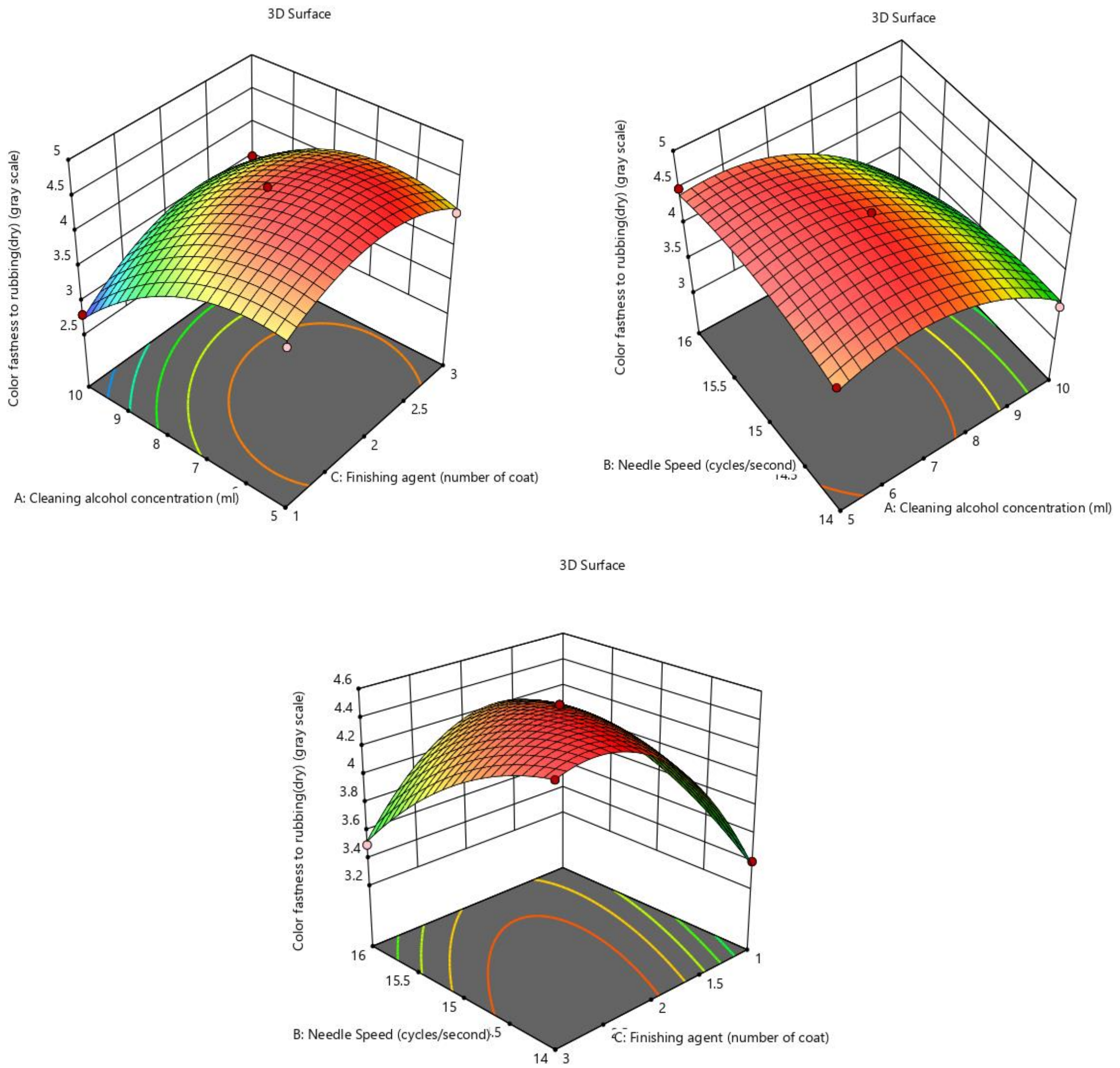

Figure 6. 3D plot graph of color fastness to rubbing (dry) to the other two factors

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.

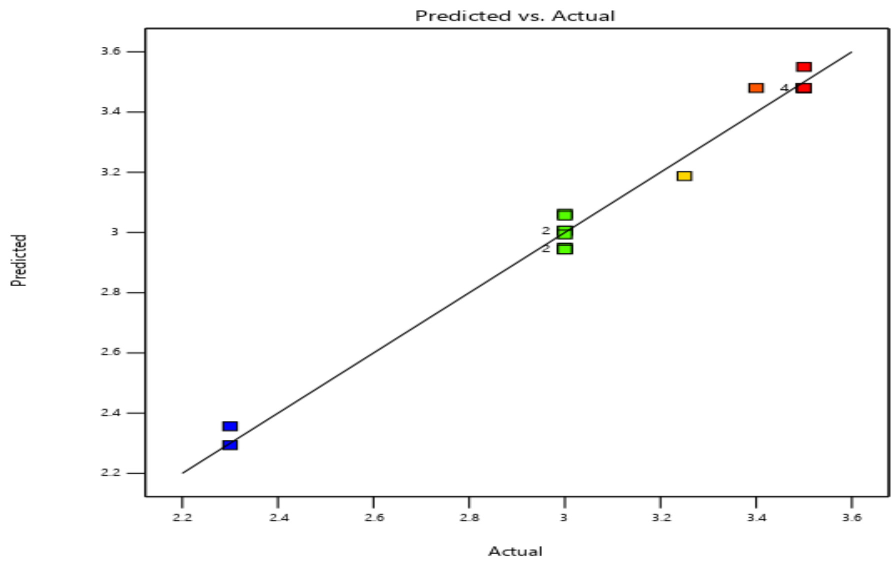

Figure 7. Color rub fastness (wet) predicted vs actual graph

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).

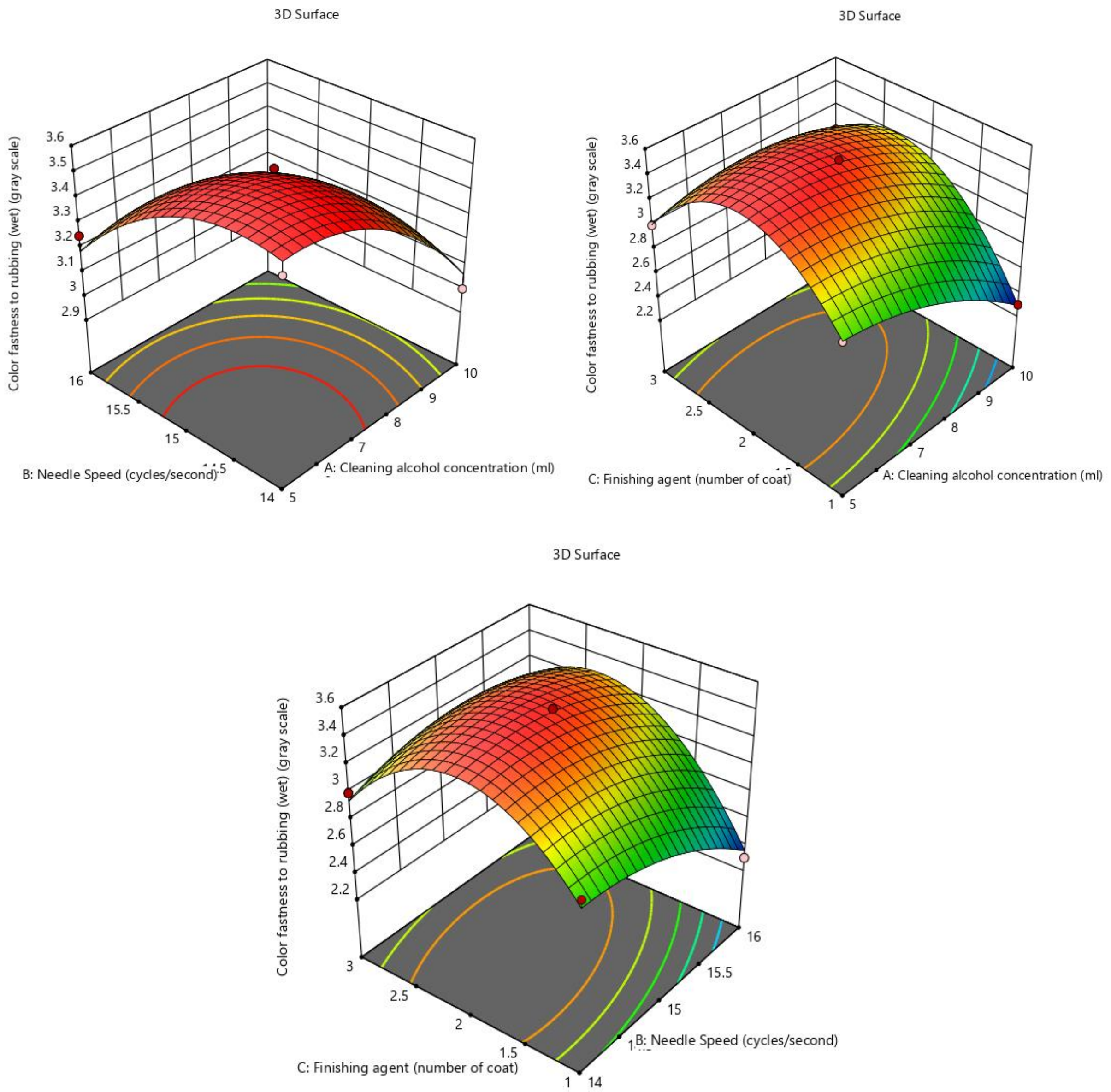

Figure 8. 3D plot graph of color fastness to rubbing (wet), to the other two factors

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 cm^2 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/mm^2), which is due to the action of mimosa tannins. Following tattooing, there was a slight decrease in tensile strength to 17.3 N/mm^2. 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.

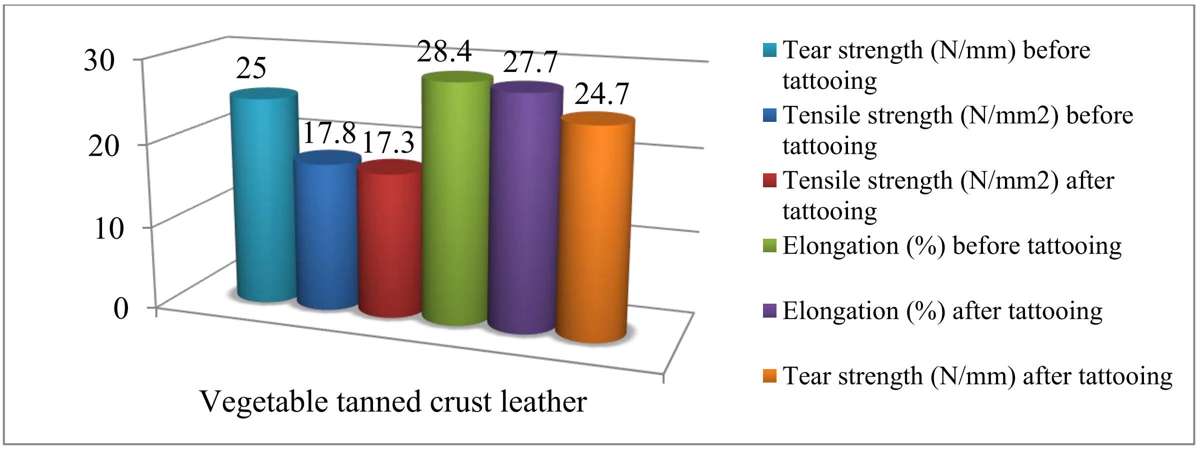

Figure 9. Mechanical properties of leather before and after tattooing

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 -CH2- and -CH3 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 C=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 -CH2- and -CH3 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 cm^{-1}). An alteration to the collagen structure caused by the ink was suggested by changes in the amide regions (1538, 1626 cm^{-1}), hydroxyl groups (3287 cm^{-1}) from residual water, ink components, or changed collagen, as well as aliphatic chains (1433, 2919 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.

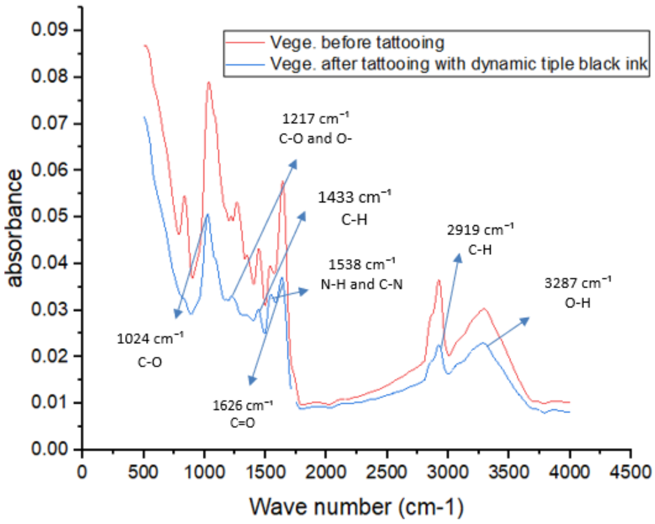

Figure 10. IR spectrograms of leather before and after tattooing

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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SYNTHESIS OF CHITOSAN BEADS/ACTIVE CHARCOAL AS ADSORBENT OF YELLOW ACID 25 AND ACID RED 73

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SYNTHESIS OF CHITOSAN BEADS/ACTIVE CHARCOAL AS ADSORBENT OF YELLOW ACID 25 AND ACID RED 73

ABSTRACT. Synthesis of chitosan/activated carbon beads has been carried out as an adsorbent for Acid Yellow 25 and Acid Red 73 in the solution. The adsorbent preparation was carried out by dissolving chitosan in 2.5% (v/v) acetic acid and then adding activated carbon. The beads were printed in NaOH solution and then washed until neutral. Chitosan/activated carbon bead adsorbents were characterized using FTIR and SEM before and after the adsorption-desorption process. Optimum conditions were determined by adsorption studies at various contact times, initial concentrations, and pH for each dye. Desorption studies were carried out using NaOH desorption medium at various concentrations and desorption times. The results showed that the optimum adsorption conditions for AY-25 were a contact time of 90 minutes with an initial concentration of 600 mg L^{-1} at pH 4 which resulted in an adsorption capacity of 501.8 mg g^{-1}. Meanwhile, AR-73 was optimum at 120 minutes with an initial concentration of 300 mg L^{-1} at pH 4 which resulted in an adsorption capacity of 297.5 mg g^{-1}. The adsorption of the two dyes followed the pseudo-second-order kinetic model and agreed with the Langmuir isotherm model. The effective desorption process was carried out with 1 M NaOH for 3 hours. The regenerated adsorbent can be used for the adsorption process three times.

KEYWORDS: adsorption, chitosan beads/activated carbon, Acid Yellow 25, Acid Red 73

SINTEZA PERLELOR DE CHITOSAN/CĂRBUNE ACTIV CA ADSORBANT PENTRU COLORANȚII ACID YELLOW 25 ȘI ACID RED 73

REZUMAT. S-a realizat sinteza perlelor de chitosan/cărbune activ ca adsorbant pentru coloranții Acid Yellow 25 și Acid Red 73 în soluție. Adsorbantul a fost preparat prin dizolvarea chitosanului în acid acetic 2,5% (v/v) și apoi adăugarea de cărbune activ. Granulele au fost impregnate în soluție de NaOH și apoi spălate până la pH neutru. S-au caracterizat adsorbanții sub formă de granule de chitosan/cărbune activat folosind FTIR și SEM înainte și după procesul de adsorbție-desorbție. Condițiile optime au fost determinate prin studii de adsorbție la diferiți timpi de contact, concentrații inițiale și pH pentru fiecare colorant. Studiile de desorbție au fost efectuate folosind mediu de desorbție NaOH la diferite concentrații și timpi de desorbție. Condițiile optime de adsorbție pentru AY-25 au fost, conform rezultatelor, un timp de contact de 90 de minute cu o concentrație inițială de 600 mg L^{-1} la pH 4, ceea ce a dus la o capacitate de adsorbție de 501,8 mg g^{-1}. Pe de altă parte, AR-73 a fost optim la un timp de contact de 120 de minute, cu o concentrație inițială de 300 mg L^{-1} la pH 4, ceea ce a dus la o capacitate de adsorbție de 297,5 mg g^{-1}. Adsorbția celor doi coloranți a urmat modelul cinetic de ordinul doi și a fost în acord cu modelul izoterm Langmuir. S-a realizat un proces de desorbție eficient folosind NaOH 1 M timp de 3 ore. Adsorbantul regenerat poate fi utilizat de trei ori pentru procesul de adsorbție.

CUVINTE CHEIE: adsorbție, granule de chitosan/cărbune activ, colorant Acid Yellow 25, colorant Acid Red 73

LA SYNTHÈSE DE BILLES DE CHITOSANE/CHARBON ACTIF COMME ADSORBANT POUR LES COLORANTS ACID YELLOW 25 ET ACID RED 73

RÉSUMÉ. La synthèse de billes de chitosane/charbon actif a été réalisée comme adsorbant pour les colorants Acid Yellow 25 et Acid Red 73 dans la solution. La préparation de l'adsorbant a été réalisée en dissolvant du chitosane dans de l'acide acétique à 2,5 % (v/v), puis en ajoutant du charbon actif. Les billes ont été imprimées dans une solution de NaOH puis lavées jusqu'à neutralité. Les adsorbants chitosane/billes de charbon actif ont été caractérisés par FTIR et SEM avant et après le processus d'adsorption-désorption. Les conditions optimales ont été déterminées par des études d'adsorption à différents temps de contact, concentrations initiales et pH pour chaque colorant. Des études de désorption ont été réalisées en utilisant un milieu de désorption NaOH à différentes concentrations et temps de désorption. Les résultats ont montré que les conditions optimales d'adsorption pour le colorant AY-25 étaient un temps de contact de 90 minutes avec une concentration initiale de 600 mg L^{-1} à pH 4, ce qui aboutissait à une capacité d'adsorption de 501,8 mg g^{-1}. D'autre part, le colorant AR-73 était optimal à 120 minutes avec une concentration initiale de 300 mg L^{-1} à pH 4, ce qui entraînait une capacité d'adsorption de 297,5 mg g^{-1}. L'adsorption des deux colorants suivait le modèle cinétique de pseudo-second ordre et était en accord avec le modèle isotherme de Langmuir. Le processus de désorption efficace a été réalisé avec du NaOH 1 M pendant 3 heures. L'adsorbant régénéré peut être utilisé pour le processus d'adsorption trois fois.

MOTS CLÉS : adsorption, billes de chitosane/charbon actif, colorant Acid Yellow 25, colorant Acid Red 73

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INTRODUCTION

Colored waste is one of the environmental problems that arise as a result of industrial activities. The dyes contained in the waste make it difficult to degrade in the environment because they tend to be stable against light and oxidizing agents and can survive under anaerobic conditions [1]. If this colored waste is disposed of into the environment, it can be harmful because of the potential toxicity carried by dyes [2]. In addition, dyes that enter the waters can block the penetration of sunlight so they must be prevented from entering water bodies and causing disruption of the ecological balance and the process of photosynthesis [3–5]. Examples of dyes commonly used in the textile and leather tanning industries are Acid Yellow 25 (AY-25) and Acid Red 73 (AR-73). Both of these dyes are included in the anionic dyes which have toxic potential in the environment.

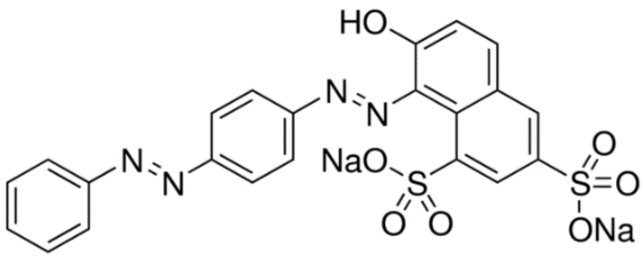


Figure 1. Structure of AY-25

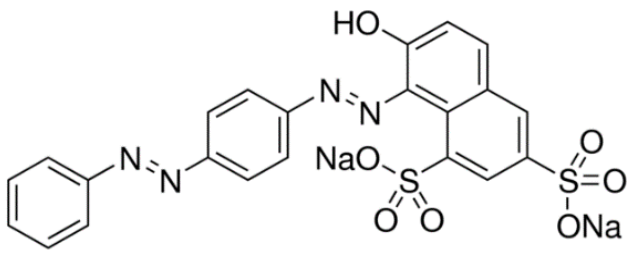


Figure 2. AR-73 structure

Waste-containing dyes can be treated by various methods, including ion exchange [6], ozonation [7-8], photocatalyst [9, 10], electrochemistry [2], oxidation [5], and adsorption [11-13]. In general, these methods can be used for the processing of dyes, but have some drawbacks, including requiring a large amount of energy, using chemical additives, and producing intermediates during the reaction.

Chitosan is the result of the deacetylation of chitin which has many applications. The use of chitosan, which is quite flexible, in various fields is due to its biodegradable nature, high compatibility, specific functional groups, low toxicity, and large enough molecules [4]. Characteristics of chitosan that can be utilized in the adsorption process are the presence of hydroxy and amine groups. However, chitosan has weaknesses such as forming colloids when in contact with water, being soluble in acids and very easily biodegradable. Therefore, to overcome these weaknesses, chitosan is usually modified by adding cross-linking agents or by impregnation, one of which is with carbon material [14, 15]. Several studies have been carried out using chitosan as an adsorbent, including the use of chitosan-silica for the adsorption of azo dyes with the adsorption parameters studied including the effect of contact time, initial adsorbate concentration, composition, and studies related to desorption [16]. Chitosan modified with activated carbon to form beads can be used for adsorption under the influence of pH. This is due to the electrostatic interaction between the charged adsorbate and the adsorbent at a certain pH [17].

EXPERIMENTAL

Materials and Methods

Materials

Chitosan and activated carbon with technical grades as well as chemicals produced by MERCK with analytical degrees of purity which include glacial acetic acid (CH_3COOH), sodium hydroxide (NaOH), and hydrochloric acid (HCl). In addition, Acid Yellow 25 (AY-25), Acid Red 73 (AR-73), and distilled water were used as solvents and washers.

Methods

Synthesis and Characterization of Chitosan/Activated Carbon Beads

1 g of chitosan was dissolved in 60 mL CH_3COOH 2.5% (v/v) and then stirred until all dissolved. Then, 1 g of activated carbon was added to the chitosan solution while stirring for 60 minutes. The resulting suspension was then dripped into 200 mL of 2.5% (w/v) NaOH solution and allowed to stand for 24 hours. The resulting beads are then washed with distilled water until the pH of the distilled water before and after washing is the same. The resulting chitosan/activated carbon beads were then dried at 100 °C. Chitosan/activated carbon beads were characterized by FTIR and SEM before and after the adsorption-desorption process.

Determination of Contact Time and Optimum Initial Concentration

A total of 0.025 g of adsorbent was added to 25 mL of AY-25 and AR-73 solutions each with a solution concentration of 100 mg L^{-1}. After that, stirring was carried out with a magnetic stirrer for 10 minutes, then the concentrations of AY-25 and AR-73 were measured after the adsorption process using a Uv-Vis Spectrophotometer with λ=393 nm (AY-25) and 512 nm (AR-73). Action steps were repeated for time variations of 20, 30, 45, 60, 90, 120, 180, 240, and 480 minutes with various concentrations of 50, 100, 200, 300, 450, 600, 800, and 1000 mg L^{-1}.

Optimum pH Determination

A total of 0.025 g of adsorbent was added to 25 mL of AY-25 and AR-73 solutions with pH 2, 4, 6, 8, and 10, respectively with various concentrations of 50, 100, 200, 300, 450, 600, 800, and 1000 mg L^{-1}. After that, adsorption was carried out during the optimum time. The next step is measuring the concentration of the dye after the adsorption process.

Adsorbent Desorption and Regeneration Studies

AY-25 and AR-73 solutions were prepared at optimum concentration conditions. The solution was used for adsorption with the adsorbent at the optimum time and pH conditions, respectively. Furthermore, the used chitosan/activated carbon adsorbent beads were dried and then used for desorption studies.

Desorption studies were carried out in 0.5 M NaOH and 1 M NaOH solutions for 1 and 3 hours. The desorption solution was then analyzed using a UV-Vis spectrophotometer. The adsorbent that has been used for desorption studies is then dried. These adsorbents were reused for the adsorption process of AY-25 and AR-73 under their respective optimum conditions. This procedure is repeated until the adsorbent is no longer effective for the adsorption process.

RESULTS AND DISCUSSIONS

Characterization of Chitosan/Activated Carbon Beads

FTIR spectra of chitosan/activated carbon beads show an absorption peak at wave number 3314 cm^{-1} which describes the stretching vibration of the –OH group which overlaps with the NH group, 2876 cm^{-1}, indicating the stretching vibration of -CH, 1573 cm^{-1} which is the bending vibration –NH2, 1369 cm^{-1} is the bending vibration absorption of –CH groups in –CHOH, and the absorption peak at 1019 cm^{-1} is the stretching vibration of –CO in CONH. After adsorption, new absorption peaks appeared at wave numbers 1186 and 808 cm^{-1} for AY-25 and

1171 and 844 cm^{-1} for AR-73. The absorption peaks at 1186 and 1171 cm^{-1} indicated the presence of –C–N=N–C– bonds of the dye molecule and 808 and 844 cm^{-1} for –C–S stretching vibrations of SO_3. The FTIR spectra of the adsorbent after desorption shown in Figure 3 shows the disappearance of the absorption peak –C–N=N–C–. This indicates that the desorption process with NaOH is effective enough to release dye molecules from the chitosan/activated carbon bead adsorbent although there are still dye molecules remaining on the surface of the adsorbent as indicated by the presence of –CS stretching vibration absorption peaks. This is in line with previous research which showed a shift in wave number and a new absorption peak after the adsorption of Yellow 42 dye [18].

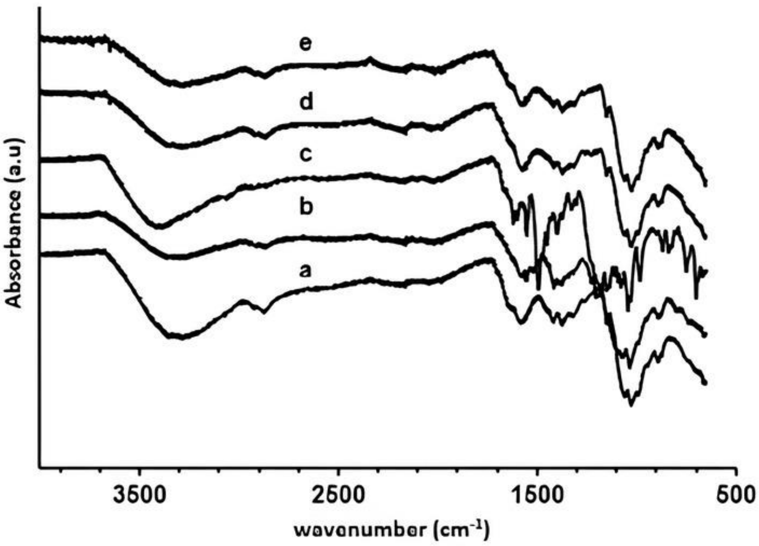
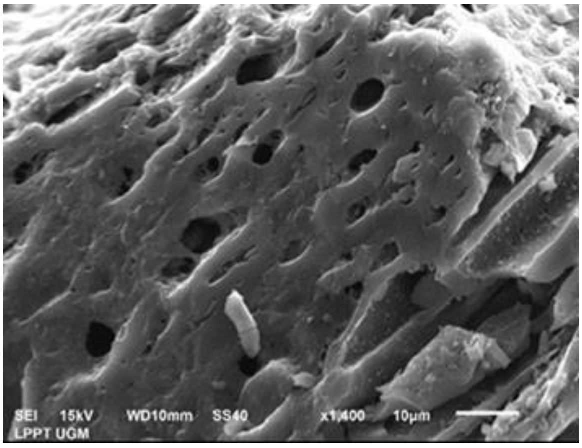
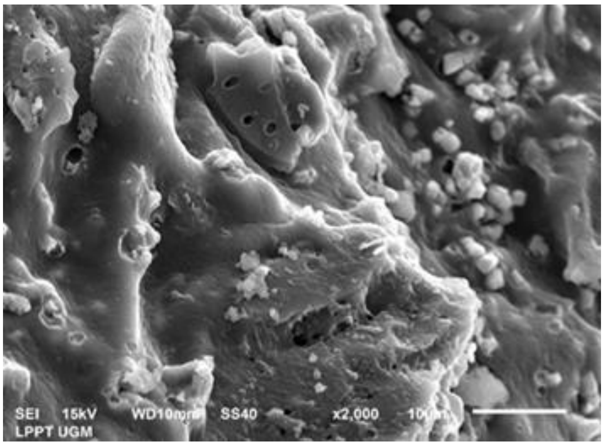


Figure 3. FTIR spectra of: a) chitosan bead/activated carbon adsorbent, b) adsorption of AY-25, c) adsorption of AR-73, d) desorption of AY-25, e) desorption of AR-73

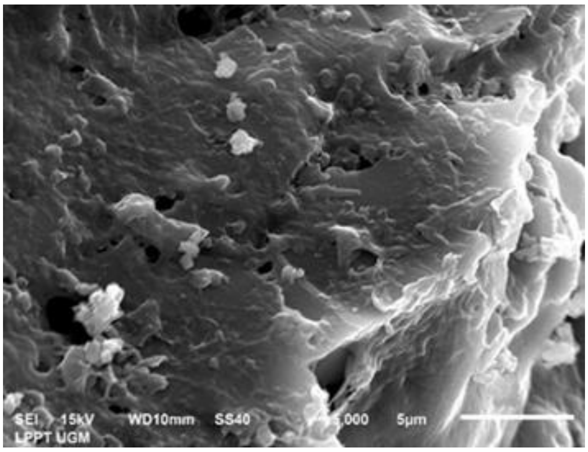
Figure 4 shows that the chitosan/activated carbon beads have pores of various sizes with irregular shapes. This pore can be used to adsorb dye molecules. Whereas the adsorbent that has been used for adsorption shows that the surface of the adsorbent becomes rougher and some lumps cover the pores. This indicates the presence of AY-25 and AR-73 molecules attached to the surface of the adsorbent. SEM image after desorption shows a smoother surface but there are still lumps attached to the surface of the adsorbent. This indicates that the desorption process still leaves dye molecules. This indication is supported by the EDX data in Table 1 which shows a decrease in the percentage of element S originating from AY-25 and AR-73 molecules in the adsorbent after the desorption process.



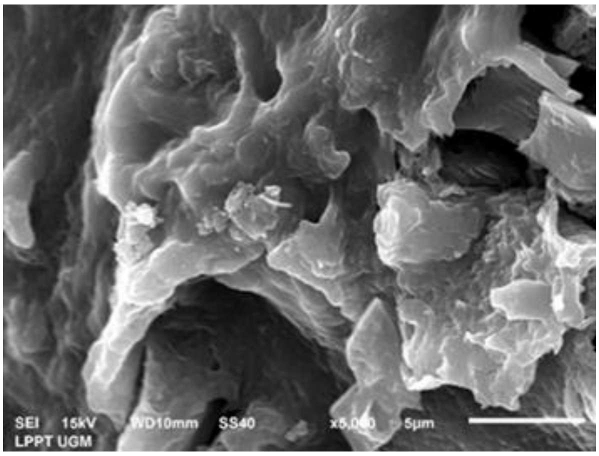
(a)



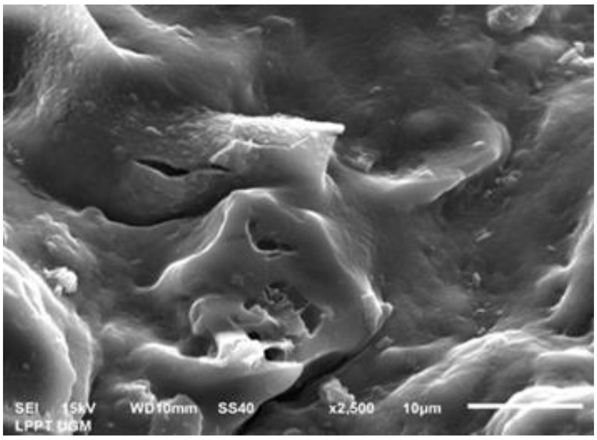
(b)



(c)



(d)



(e)

Figure 4. SEM images of: a) chitosan bead/activated carbon adsorbent, b) after adsorption of AY-25, c) after adsorption of AR-73, d) after desorption of AY-25, and e) after desorption of AR-73

Table 1: EDX data before and after the adsorption-desorption process of AY-25 and AR-73

Element	Pristine Adsorbent (%)	Ads AY-25 (%)	Δ% Ads AY-25	Ads AR-73 (%)	Δ% Ads AR-73	Des AY-25 (%)	Δ% Des AY-25	Des AR-73 (%)	Δ% Des AR-73
C	46.32	48.20	+4.06%	53.51	+15.52%	46.13	−0.41%	50.26	+8.50%
N	19.85	20.97	+5.64%	19.78	−0.35%	20.18	+1.66%	19.66	−0.96%
O	33.43	29.33	−12.27%	25.66	−23.24%	32.85	−1.74%	28.85	−13.70%
S	–	1.14	Detected	0.47	Detected	0.34	Residual	0.37	Residual

Determination of Contact Time and Optimum Concentration

Based on Figure 5a and Figure 5b it can be seen that the adsorption capacity increased significantly at the beginning of the process, then tended to be constant. Optimum conditions for AY-25 adsorption occurred at a contact time of 90 minutes and for AR-73 occurred at a contact time of 120 minutes. The increase in adsorption capacity at the beginning of the process occurs because the adsorbate attaches to the active site of the adsorbent which is still empty so that the dye molecules diffuse more easily on the surface of the adsorbent. The adsorption capacity of AY-25 and AR-73 increased with increasing contact time, but after the optimum contact time, the adsorption capacity tended to be constant. This happens because the number of active sites that are empty on the adsorbent has decreased [19].

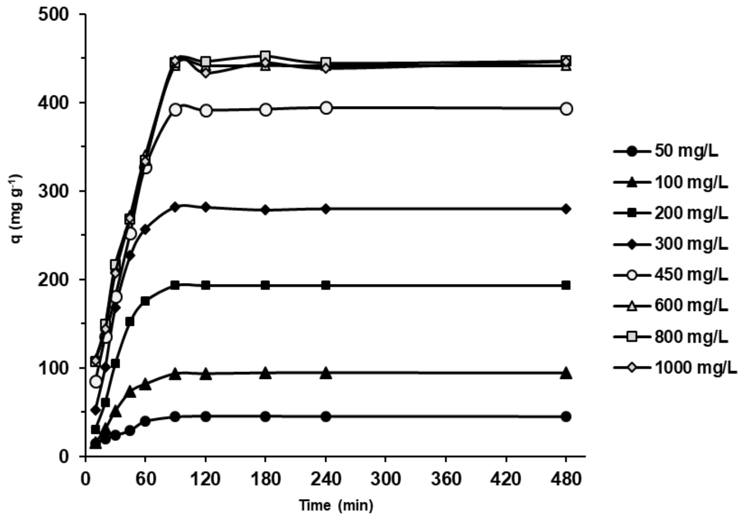


Figure 5a. Graph of determination of contact time and initial concentration of AY-25

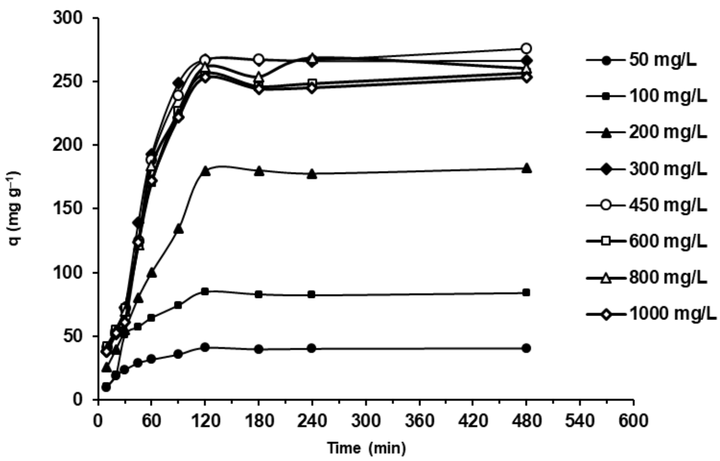


Figure 5b. Graph of determination of contact time and initial concentration of AR-73

The difference in the optimum time between AY-25 and AR-73 is due to the difference in the adsorption rate of the two dyes. Adsorption speed or rate can be determined using kinetic equations. This study uses first-order, second-order, pseudo-first-order, and pseudo-second-order kinetic equations. A summary of the parameters of various kinetic models is presented in Table 2.

Table 2: Adsorption kinetics parameters of AY-25 and AR-73 in solution on chitosan/activated carbon beads

Kinetic Models	Parameter	AY-25	AR-73
q_e experiment (mg g^{-1})		442.53	267.38
Order one	k'_1 (min^{-1})	2.6×10^{-3}	4.6×10^{-3}
	R^2	0.5354	0.5240
Order two	k'_2 (min^{-1})	1.0×10^{-5}	6.0×10^{-5}
	R^2	0.5963	0.5607
Pseudo first order	k_1 (min^{-1})	0.0143	0.0137
	R^2	0.4887	0.5568
	q_e calculation (mg g^{-1})	79.51	88.23
Pseudo second order	k_2 (g mg^{-1} min^{-1})	7.9×10^{-5}	5.5×10^{-5}
	R^2	0.9917	0.9564
	q_e calculation (mg g^{-1})	476.19	312.50
	H	17.96	5.43

Table 3: Parameters of Langmuir and Freundlich isotherms for adsorption of AY-25 and AR-73

Model	Parameter	AY-25	AR-73
	q_{max} experiment (mg g^{-1})	442.53	267.38
Freundlich	K_f	52.79	44.27
	1/n	2.56	3.29
	R^2	0.7011	0.5556
Langmuir	K_L (L mg^{-1})	0.04	0.08
	R_L	0.02	0.01
	q_{max} (mg g^{-1})	476.19	263.16
	R^2	0.9950	0.9949

The kinetic model suitable for the adsorption of AY-25 and AR-73 is a pseudo-second-order kinetic model. One of the things that affect the rate of adsorption is the size of the adsorbate molecule [20]. AY-25 with a molecular weight of 549.55 g mol^{-1} which is smaller than AR-73 with a molecular weight of 556.48 g mol^{-1} causes AY-25 to diffuse faster than AR-73. This is supported by data on the optimum contact time for AY-25 which is faster than AR-73.

Other parameters determined in this study were the initial concentrations of AY-25 and AR-73. Figures 5a and 5b show that the adsorption capacity increases as the adsorbate concentration increases, then at a certain concentration it tends to be constant. A significant increase in adsorption capacity at the beginning of adsorption was caused by an increase in the concentration of the adsorbate, causing a concentration gradient that accelerated diffusion [21]. This research resulted that the optimum initial concentration of AY-25 was 600 mg L^{-1} while AR-73 had an optimum initial concentration of 300 mg L^{-1}.

One way to determine the type of interaction between adsorbate and adsorbent is through the determination of isotherms that describe adsorption capacity as a function of the equilibrium concentration of adsorbate at a constant temperature [22]. The isotherms studied in this study are Langmuir and Freundlich isotherms. Parameter data for Langmuir and Freundlich isotherms are presented in Table 3 which shows that the appropriate coefficient of determination is the Langmuir isotherm for the adsorption of AY-25 and AR-73. The agreement with the Langmuir isotherm indicates that the maximum adsorption of AY-25 and AR-73 occurs when a monolayer layer is formed on the surface of the adsorbent with constant adsorption energy and there is no interaction between the adsorbate molecules and neighboring active sites [22, 23]. This study indicated that the adsorption was influenced by the interaction between the sulfonate groups of the dye molecules and the amino groups of chitosan.

Optimum pH Determination

Figures 6a and 6b show that pH 4 is the optimum pH for the adsorption of AY-25 and AR-73. The figure also shows a tendency to decrease the adsorption capacity of the two dyes as the pH increases. This occurs because at low pH conditions the increased concentration of H^+ ions promotes the protonation of amino groups on the adsorbent surface ($-NH_2$ to $-NH_3^+$), leading to a positively charged surface that enhances electrostatic interactions with negatively charged adsorbate molecules, although ζ-potential measurements were not performed in this study [24, 25]. Chitosan in a low pH environment will cause the protonated $-NH_2$ group to become $-NH^{3+}$ [24]. Therefore, the electrostatic interaction between the adsorbate in the form of anionic dyes and the adsorbent will take place optimally at low pH. The decrease in adsorption capacity when there is an increase in pH is due to the fact that at a pH that tends to be neutral, chitosan will tend to form $-NH_2$ compared to $-NH^{3+}$ so that it will be more difficult to bind to anionic dyes [25]. An increase in pH also causes the number of OH- ions to increase, causing competition with anionic dye molecules [26].

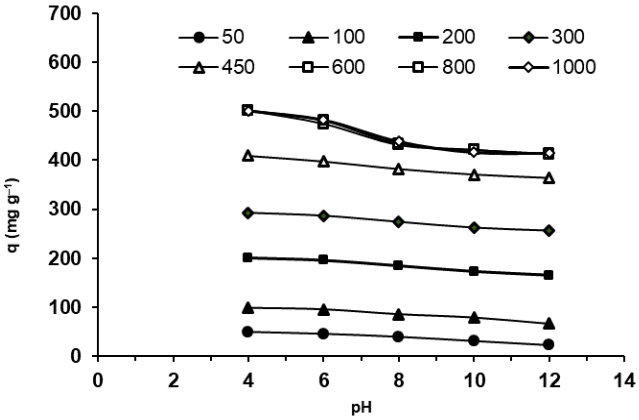


Figure 6a. Graph of determining the optimum pH of AY-25

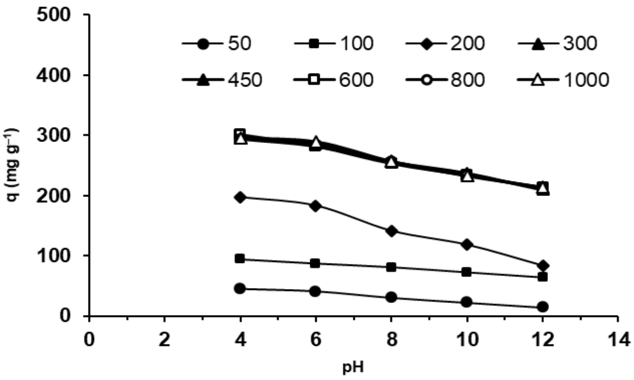


Figure 6b. Graph of determining the optimum pH of AR-73

Desorption Study

Figure 7 shows that as the NaOH concentration and desorption time increased, the amount of AY-25 and AR-73 released increased. This is caused by the weakening of the electrostatic interaction of the sulfonate groups of dyes with chitosan due to an increase in pH which causes chitosan to tend to form $-NH_2$ resulting in the release of adsorbate molecules [26]. From these results, it can be predicted that the most dominant interaction in the adsorption of AY-25 and AR-73 using chitosan/activated carbon beads is the electrostatic interaction of the dye sulfonate groups with $-NH^{3+}$ from chitosan in an acidic condition. The highest desorption percentages of AY-25 and AR-73 were produced by 1 M NaOH desorption solution with a desorption time of 3 hours, namely 50.57% for AY-25 and 57.60% for AR-73.

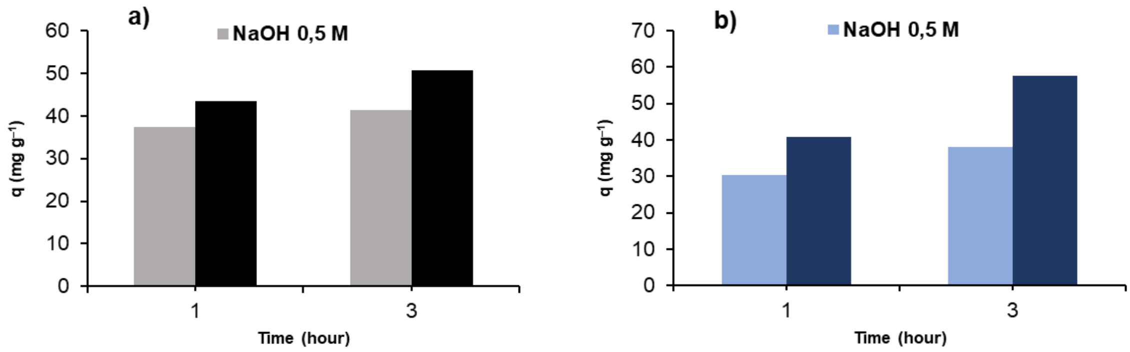


Figure 7. Desorption percentage of (a) AY-25 and (b) AR-73 at different desorption times using NaOH solutions of two concentrations; the darker bars represent 1.0 M NaOH, while the lighter bars represent 0.5 M NaOH

CONCLUSIONS

This research produced chitosan/ activated carbon beads which could be used as dye adsorbents for Acid Yellow 25 and Acid Red 73 with the optimum contact time for AY-25 adsorption at 90 minutes while for AR-73 at 120 minutes. Adsorption of both dyes followed a pseudo second-order kinetic model. The adsorption capacity of both dyes increased with an increasing initial concentration of the solution and optimally took place at pH 4. Chitosan/activated carbon bead adsorbents using NaOH would result in an increase in percent desorption with increasing concentration and time. The regenerated chitosan/carbon bead adsorbent can be reused for adsorption three times.

Conflict of Interests

No potential conflict of interest was stated by the authors.

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CHALLENGES IN PROTECTIVE FOOTWEAR FOR INDIA'S DISASTER MANAGEMENT WORKFORCE: A DESIGN THINKING APPROACH

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CHALLENGES IN PROTECTIVE FOOTWEAR FOR INDIA'S DISASTER MANAGEMENT WORKFORCE: A DESIGN THINKING APPROACH

ABSTRACT. Firefighters in India play a critical role in managing fire accidents and rescue operations, often working under high-pressure and hazardous conditions. Their work demands swift and efficient action, making it essential to ensure their safety and performance through appropriate equipment, particularly footwear. Footwear is a crucial component of their protective gear, directly impacting their mobility, comfort, and overall effectiveness during rescue operations. This study explores the current challenges associated with the footwear used by disaster management professionals in India, with a specific focus on firefighters. It evaluates the design, functionality, and performance of the footwear currently in use and identifies the limitations that hinder their effectiveness in extreme conditions. The research adopts a design thinking approach to analyze the challenges faced by disaster management professionals through a comprehensive mixed-methods study. A structured survey was conducted with 385 disaster management professionals across Six Indian states (Telangana, Maharashtra, Karnataka, Tamil Nadu, west Bengal and Gujarat), complemented by in-depth interviews with 75 firefighters from various operational levels. Additionally, a systematic literature review was conducted. Data were gathered on various factors, including comfort, durability, protection, flexibility, and environmental adaptability of the footwear. Findings reveal near-unanimous consensus on the need for footwear redesign, with 96.1% of respondents in agreement. Poor heat and flame resistance emerged as the dominant performance deficiency, identified by 34.8% of respondents. Chi-square analysis confirmed a highly significant association between reported challenges and redesign necessity ($\chi^2 = 28.47$, $p < 0.001$, Cramér's $V = 0.272$). K-means cluster analysis identified three operationally distinct user personas, affirming that a single uniform specification is insufficient for India's heterogeneous disaster management workforce. Evidence-based design specifications were translated into two functionally differentiated prototypes. Design A, a low-mid ankle boot incorporating the patent-pending Protected Rapid-Release Closure System, achieved full IS 15298 (Part 2):2024 compliance across all mandatory test parameters, with breathability exceeding Indian market norms. Design B, a tall shaft boot configured for wildland deployment, incorporated an external TPU ankle panel with documented protection-mobility trade-offs. Both prototypes were validated at a BIS-approved laboratory, utilising an Indian-specific anthropometric last and a nine-component material architecture, demonstrating the feasibility of IS 15298-compliant next-generation protective footwear within Indian manufacturing constraints.

KEYWORDS: firefighting footwear design, protective footwear, occupational safety, design thinking, ergonomics, India disaster management

PROVOCĂRI LEGATE DE ÎNCĂLȚĂMINTEA DE PROTECȚIE PENTRU PERSONALUL DE GESTIONARE A CATASTROFELOR DIN INDIA: O ABORDARE BAZATĂ PE DESIGN THINKING

REZUMAT. Pompierii din India joacă un rol esențial în gestionarea incendiilor și în operațiunile de salvare, lucrând adesea în condiții periculoase și de mare presiune. Munca acestora necesită acțiuni rapide și eficiente, fiind esențial să li se asigure siguranța și performanța prin echipamente adecvate, în special încălțăminte. Încălțămintea este o componentă crucială a echipamentului lor de protecție, având un impact direct asupra mobilității, confortului și eficienței generale în timpul operațiunilor de salvare. Acest studiu explorează provocările actuale asociate încălțămintei utilizate de profesioniștii din domeniul gestionării dezastrelor din India, cu un accent specific pe pompieri. Articolul evaluează designul, funcționalitatea și performanța încălțămintei utilizate în prezent și identifică limitările care le împiedică eficacitatea în condiții extreme. Cercetarea adoptă o abordare de tip design thinking pentru a analiza provocările cu care se confruntă profesioniștii din domeniul gestionării dezastrelor printr-un studiu cuprinzător bazat pe metode mixte. S-a realizat un sondaj structurat cu 385 de profesioniști în gestionarea dezastrelor din șase state federale indiene (Telangana, Maharashtra, Karnataka, Tamil Nadu, Bengalul de Vest și Gujarat), completat de interviuri aprofundate cu 75 de pompieri de la diferite niveluri operaționale. În plus, s-a efectuat o analiză sistematică a literaturii de specialitate. Au fost colectate date privind diverși factori, printre care confortul, durabilitatea, protecția, flexibilitatea și adaptabilitatea la condițiile de mediu a încălțămintei. Rezultatele indică un consens aproape unanim cu privire la necesitatea reproiectării încălțămintei, 96,1% dintre respondenți fiind de acord cu acest lucru. Rezistența slabă la căldură și la foc s-a evidențiat ca fiind principala deficiență de performanță, identificată de 34,8% dintre respondenți. Analiza chi-pătrat a confirmat o asociere extrem de semnificativă între provocările raportate și necesitatea reproiectării ($\chi^2 = 28{,}47$, $p < 0{,}001$, coeficientul V Cramér = 0,272). Analiza clusterelor K-means a identificat trei tipuri de utilizatori distincte din punct de vedere operațional, confirmând faptul că o singură specificație uniformă este insuficientă pentru forța de muncă eterogenă din domeniul gestionării dezastrelor din India. Specificațiile de proiectare bazate pe dovezi au fost transpuse în două prototipuri diferențiate din punct de vedere funcțional. Modelul A, o gheată joasă-medie care încorporează sistemul de închidere rapidă protejat (în curs de brevetare), în conformitate deplină cu IS 15298 (Partea 2):2024 pentru toți parametrii de testare obligatorii, cu o respirabilitate care depășește normele pieței indiene. Modelul B, o cizmă înaltă configurată pentru utilizare în zone sălbatice, a încorporat un panou extern din TPU la nivelul gleznei, cu compromisuri documentate între protecție și mobilitate. Ambele prototipuri au fost validate într-un laborator aprobat de BIS, utilizând o formă antropometrică specifică pentru India și o arhitectură a materialelor cu nouă componente, demonstrând fezabilitatea încălțămintei de protecție de nouă generație conformă cu IS 15298 în cadrul producției indiene.

CUVINTE CHEIE: proiectarea încălțămintei pentru pompieri, încălțăminte de protecție, securitatea muncii, design thinking, ergonomie, gestionarea dezastrelor în India

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LES DÉFIS LIÉS AUX CHAUSSURES DE PROTECTION POUR LE PERSONNEL CHARGÉ DE LA GESTION DES CATASTROPHES EN INDE : UNE APPROCHE BASÉE SUR LE DESIGN THINKING

RÉSUMÉ. En Inde, les pompiers jouent un rôle essentiel dans la gestion des incendies et les opérations de sauvetage, travaillant souvent dans des conditions de forte pression et dangereuses. Leur travail exige une intervention rapide et efficace, d'où la nécessité de garantir leur sécurité et leur performance grâce à un équipement adapté, en particulier des chaussures. Les chaussures constituent un élément crucial de leur équipement de protection, ayant un impact direct sur leur mobilité, leur confort et leur efficacité globale lors des opérations de sauvetage. Cette étude explore les défis actuels liés aux chaussures utilisées par les professionnels de la gestion des catastrophes en Inde, en mettant particulièrement l'accent sur les pompiers. Elle évalue la conception, la fonctionnalité et les performances des chaussures actuellement utilisées et identifie les limites qui entravent leur efficacité dans des conditions extrêmes. La recherche adopte une approche de « design thinking » pour analyser les défis auxquels sont confrontés les professionnels de la gestion des catastrophes à travers une étude mixte exhaustive. Une enquête structurée a été menée auprès de 385 professionnels de la gestion des catastrophes dans six États indiens (Telangana, Maharashtra, Karnataka, Tamil Nadu, Bengale occidental et Gujarat), complétée par des entretiens approfondis avec 75 pompiers issus de différents niveaux opérationnels. De plus, une revue systématique de la littérature a été réalisée. Des données ont été recueillies sur divers facteurs, notamment le confort, la durabilité, la protection, la souplesse et l'adaptabilité environnementale des chaussures. Les résultats révèlent un consensus quasi unanime sur la nécessité de repenser la conception des chaussures, 96,1 % des personnes interrogées partageant cet avis. La faible résistance à la chaleur et aux flammes est apparue comme la principale lacune en matière de performance, signalée par 34,8 % des personnes interrogées. L'analyse du chi carré a confirmé une association hautement significative entre les défis signalés et la nécessité d'une refonte (χ^2 = 28,47, p < 0,001, V de Cramér = 0,272). L'analyse en grappes K-means a identifié trois profils d'utilisateurs distincts sur le plan opérationnel, confirmant qu'une spécification unique et uniforme est insuffisante pour le personnel hétérogène chargé de la gestion des catastrophes en Inde. Les spécifications de conception fondées sur des données probantes ont été traduites en deux prototypes fonctionnellement différenciés. Le modèle A, une bottine mi-haute intégrant le système de fermeture à dégagement rapide protégé (brevet en instance), a atteint la conformité totale à la norme IS 15298 (Partie 2):2024 pour tous les paramètres de test obligatoires, avec une respirabilité qui dépasse les normes du marché indien. Le modèle B, une botte à tige haute conçue pour les interventions en milieu naturel, intégrait un renfort de cheville externe en TPU avec des compromis documentés entre protection et mobilité. Les deux prototypes ont été validés dans un laboratoire agréé par le BIS, en utilisant une forme anthropométrique spécifique à l'Inde et une architecture matérielle à neuf composants, démontrant ainsi la faisabilité de chaussures de protection de nouvelle génération conformes à la norme IS 15298 dans le cadre de la fabrication indienne.

MOTS-CLÉS : conception de chaussures pour pompiers, chaussures de protection, sécurité au travail, design thinking, ergonomie, gestion des catastrophes en Inde

INTRODUCTION

Firefighting is a physically and mentally demanding profession, requiring individuals to operate in hazardous environments under time-critical conditions. As first responders, firefighters face significant risks, including exposure to high temperatures, sharp debris, unstable terrain, and toxic substances [1]. While personal protective equipment (PPE) plays a pivotal role in safeguarding firefighters, footwear is often an overlooked yet essential element of their gear.

India's disaster management workforce operates in one of the world's most challenging environments, facing diverse hazards ranging from urban fires and industrial accidents to natural disasters and complex emergency situations. According to the National Crime Records Bureau (NCRB) data from 2018–2022 and 2023, residential/dwelling buildings and other locations account for approximately 96% of fire incidents in India, with residential fires contributing 56.47% and other categories 39.53% of total incidents. This distribution indicates that approximately 96% of fire cases require Class 1 category footwear, emphasizing the critical importance of optimizing protective equipment for these scenarios.

The complexity of protective footwear design stems from competing requirements that must be simultaneously satisfied: providing adequate protection against thermal, mechanical, and chemical hazards while maintaining mobility, comfort, and rapid deployment capabilities [2, 3]. These challenges are amplified in the Indian context by diverse climatic conditions, varied operational environments, budget constraints, and the need for equipment that can be effectively maintained and replaced within existing organizational structures.

The current study investigates the footwear used by disaster management professionals in India, emphasizing design and performance limitations through comprehensive primary research across multiple states. The primary objective is to analyze challenges posed by existing footwear through statistically robust data collection and propose evidence-based recommendations for developing next-generation designs that enhance safety, comfort, and functionality.

General Requirements for PPE Footwear for Indian Firefighters

Firefighting PPE footwear must address specific environmental, operational, and safety challenges unique to the region while complying with national and global standards such as BIS (Bureau of Indian Standards) IS 15298 [4] for safety footwear and relevant sections of NFPA 1971 or ISO EN 15090 [5].

As per IS 15298-2 (2011), safety footwear for Indian firefighters is categorized based on material construction: Class I covers footwear constructed from leather or comparable materials, excluding designs made entirely of rubber or polymeric components; Class II covers fully molded or vulcanized footwear crafted from all-rubber or all-polymeric materials. Safety footwear is further classified by coverage extent into five types: Low Shoes (Type A), Ankle Boots (Type B), Half-Knee Boots (Type C), Knee-High Boots (Type D), and Thigh Boots (Type E). Performance features include heat and flame resistance, penetration-resistant midsoles, anti-slip outsoles, and electrical resistance options with additional features like water resistance, chemical resistance, and energy-absorbing cushioned heels.

Fire Classification and Equipment Requirements

Figure 1. Class 2 firefighting shoes

Figure 2. Present footwear (green & black) used – Class 1

Class 1 Fire refers to fires involving ordinary combustibles such as wood, paper, cloth, and plastics. These materials ignite easily and burn with surface flames, commonly found in residential and office settings. Class 1 fires typically require firefighting equipment that prioritizes accessibility, agility, and moderate heat resistance, with leather-based footwear construction providing sufficient protection while ensuring mobility and breathability.

Class 2 Fire involves flammable liquids and gases such as gasoline, oil, alcohol, and propane. These fires present higher hazards due to rapid spread, intense heat, and explosion potential, prevalent in industrial environments and chemical plants. Class 2 fire response requires specialized equipment including fully molded or vulcanized footwear with superior heat resistance, chemical resistance, and waterproofing capabilities.

Given that most of the of fire incidents in India fall into Class 1 category scenarios based on NCRB data, this research focuses primarily on optimizing Class 1 footwear performance while acknowledging the need for specialized Class 2 equipment in industrial contexts.

LITERATURE REVIEW

Global Challenges in Protective Footwear Design

The literature reveals multiple interconnected challenges that compromise the effectiveness and adoption of protective footwear among emergency responders worldwide. A comprehensive scoping review by Orr *et al*. [2] identified key performance limitations including bulk and weight effects on energy expenditure and obstacle clearance, restricted ankle range of motion from stiff shaft construction, and fit variability leading to user discomfort and non-compliance. Protective boots typically weigh 1.5–3.0 kg more than standard footwear, resulting in increased metabolic cost and altered gait mechanics that can elevate injury risk [2]. The thermal burden associated with multilayer protective construction compounds these challenges, particularly in hot climates where heat stress becomes a critical operational limitation.

Design Challenges and Safety Concerns

Firefighter turnout boots have been identified as significant factors impacting safety and health, with poor design leading to risks such as falls and muscular injuries [6]. Key design components like cushioning, traction, and structural support are crucial, but other factors like waterproofness and thermal comfort also need attention. Firefighting footwear must provide effective protection against hazards while being ergonomically suitable for the wearer, adapting to various working conditions and ensuring no additional risk to health [7].

Current Technologies and Materials

Modern protective footwear integrates sophisticated multilayer constructions combining textiles, reinforcements, and specialized sole compounds to meet flame, cut, electrical, and puncture resistance requirements [3, 8]. Industry standards such as NFPA 1971, EN ISO 20345, and CSA variants drive design specifications that often prioritize protection levels over ergonomic considerations. Recent innovations focus on addressing traditional limitations through advanced materials and construction techniques. Quick don/doff systems aim to reduce deployment time, while dual lacing and zipper systems provide secure fit with integrated handles for ease of use [9]. Sustainable design practices are being explored to improve environmental impact, with focus on additive technologies while meeting high standards of quality and safety [7].

India-Specific Research Context

Limited research specifically addresses Indian emergency responders' needs. Ticlo and Rao [10] conducted comprehensive studies of Indian firefighter PPE needs, revealing significant gaps in equipment provision. However, their sample size of 160 personnel, while valuable, represents a limited geographic scope requiring expansion for national-level conclusions.

METHODOLOGY

Research Design

A mixed-methods study blending design thinking (empathize, define, ideate, prototype, test) with systematic literature review and statistically validated surveys/interviews.

Sample Size & Justification

Primary empirical data were collected across six geographically distributed sites, each selected on the basis of proximity to established professional facilities, ensuring access to the target respondent population. Multi-stage purposive sampling was employed as the overarching sampling strategy. The total sample size of 385 was determined using the standard formula for population proportion estimation, computed at a 95% confidence level with a 5% margin of error.

The sites spanned six states and one union territory-adjacent region, collectively representing the northern, southern, eastern, and western zones of India. Hyderabad, Telangana, served as the primary access point, contributing 65 respondents. An equivalent allocation of 65 respondents was drawn from Nagpur, Maharashtra. The remaining four sites each contributed 64 or 63 respondents: Bengaluru, Karnataka, was accessed through city fire stations; Chennai, Tamil Nadu, and Ankleshwar, Gujarat, were engaged through locally available professional facilities; and Kolkata and the 24 Parganas district of West Bengal yielded 63 respondents. The marginal variation in sub-sample sizes across sites reflects differences in institutional access and availability of eligible respondents at the time of data collection, and does not compromise the overall representativeness of the sample.

Sampling Strategy

Distinct sampling criteria were applied for the two primary data collection instruments to ensure that respondents possessed the requisite professional experience and operational relevance.

For the survey, inclusion was restricted to active firefighters with a minimum threshold of continuous service, who were regular users of Class 1 safety footwear and engaged in operational field roles. Respondents in administrative or non-operational capacities, temporary workers, and those below the minimum experience threshold were excluded, ensuring that responses reflected substantive firsthand experience under actual field conditions.

For the in-depth interviews, purposive sampling was employed to achieve structured representation across three intersecting dimensions: operational level, ranging from junior personnel through to senior staff and officers; years of service, spanning early-career through to highly experienced professionals; and geographic context, covering urban, semi-urban, and rural deployment environments. This layered sampling approach ensured that the interview data captured a diverse range of occupational exposures, roles, and regional operational conditions encountered by disaster management professionals across India.

Survey Instrument

A rigorously validated survey instrument comprising 28 items was employed to capture respondents' demographic profile, current footwear assessment, operational challenges, priority design requirements, and material preferences. The questionnaire's content validity was established via an expert panel of five fire safety specialists, while reliability metrics demonstrated excellent internal consistency (Cronbach's alpha = 0.87) and strong test-retest stability ($r = 0.92$ over a two-week interval, $n=30$).

In-depth qualitative insights were obtained using a semi-structured interview protocol built around twelve core questions. These interviews addressed footwear performance and limitations, impacts on operational safety, challenges encountered in various environments, and experiences with injuries or near-misses. Additional probes explored respondents' recommendations for improvement, targeted design features, and considerations related to training and footwear maintenance.

Data Collection Procedures

Surveys were administered online from March–May 2024, yielding an 89.3% response rate (385/431; average completion: 18 minutes). Individual interviews (45–60 minutes) were conducted by trained researchers.

Data Analysis

Quantitative Analysis

Descriptive statistics, chi-square tests, independent t-tests, ANOVA, and correlation analyses were performed on quantitative data, with statistical significance set at $p < 0.05$.

Qualitative Analysis

Interview data were analysed through thematic analysis following Braun and Clarke's framework, using inductive coding. Inter-rater reliability was strong (Cohen's kappa = 0.89), and data saturation was confirmed by the sixty-eighth interview [11].

Ethical Considerations

The study adhered to established ethical standards throughout, encompassing informed consent, the right to withdraw, confidentiality, anonymity, and secure data management at all stages of the research process.

The interview sample was profiled across years of service and operational area. Service experience was distributed across early, mid, and long-tenure career stages, with mid-career professionals forming the largest segment. In terms of operational context, urban respondents constituted the majority, with progressively smaller representations from semi-urban and rural settings, broadly reflecting the deployment patterns of disaster management professionals across India.

Limitations and Mitigation Strategies

The study's six-state coverage may not fully represent all Indian regions, though states were selected for climatic and operational diversity; self-report bias was mitigated by triangulating data sources and validation techniques; cross-sectional design limits causality, recommending longitudinal follow-up for future research.

RESULTS AND DISCUSSION

Current Footwear Performance Assessment

Analysis of responses from 385 disaster management professionals reveals significant dissatisfaction with current class 1 footwear across multiple performance dimensions:

Table 1: Current footwear performance assessment

Challenge Category	n	%	95% CI
1. Poor heat and flame resistance	134	34.8	30.1-39.7
2. Poor grip on wet/slippery surfaces	58	15.1	11.7-19.0
3. Water absorption and permeability	46	11.9	8.9-15.6
4. Excessive weight and bulk	38	9.9	7.1-13.3
5. Limited flexibility for movement	35	9.1	6.5-12.4
6. Inadequate thermal insulation	31	8.1	5.6-11.2
7. Difficulty in quick donning/removal	28	7.3	4.9-10.3
8. Durability and wear issues	15	3.9	2.2-6.4

When respondents were asked to identify the most significant performance challenges associated with their current footwear, poor heat and flame resistance emerged as the dominant concern, cited by over one-third of the sample, underscoring the primacy of thermal protection in high-risk operational environments. Inadequate grip on wet and slippery surfaces was the second most frequently reported challenge, followed by water absorption and permeability, reflecting persistent issues with moisture management under field conditions. Excessive weight and bulk, and limited flexibility for movement, were identified by approximately one in ten respondents each, pointing to ergonomic constraints that impede operational agility. Inadequate thermal insulation and difficulty in quick donning and removal were also notable concerns, particularly given the time-critical nature of emergency deployment. Durability and wear issues, while reported by a smaller proportion, nonetheless highlight concerns regarding the long-term serviceability of current footwear. Taken together, these findings indicate that existing footwear falls short across multiple performance dimensions, with thermal and traction deficiencies representing the most pressing areas for design intervention.

Redesign Agreement Analysis

Respondent attitudes towards footwear redesign were overwhelmingly positive. A substantial majority expressed strong agreement with the need for redesign initiatives, with a further significant proportion indicating general agreement.

Agreement Distribution:

a. Strongly Agree: 251 respondents (65.2%);
b. Agree: 119 respondents (30.9%);
c. Neutral: 15 respondents (3.9%);
d. Disagree: 0 respondents (0.0%);
e. Strongly Disagree: 0 respondents (0.0%).

Combined Agreement: 370 respondents (96.1%) support footwear redesign initiatives.

Neutral responses accounted for a negligible share of the sample, and no respondents indicated disagreement or strong disagreement. The combined agreement rate of 96.1% reflects a near-unanimous consensus among operational firefighting professionals regarding the inadequacy of current footwear and the imperative for purposive redesign, lending strong empirical support to the central premise of this research.

Feature Importance Priorities

Respondents were asked to rank a set of desired features for redesigned protective footwear using a five-point Likert scale. Heat resistance up to 300°C emerged as the highest priority feature, recording the highest mean score and cited as the top priority by approximately one-third of respondents, reinforcing the findings on performance challenges where thermal protection was the dominant concern. Water resistance and lightweight design followed as the second and third ranked features respectively, reflecting the dual demand for moisture protection and ergonomic wearability. Slip resistance and comfort and breathability were ranked closely thereafter, indicating that traction and physiological comfort are considered near-equally important by operational personnel. Shock absorption and durability occupied the mid-to-lower rankings, while quick donning and doffing, though ranked last, still recorded a mean score approaching four, suggesting it remains a relevant consideration rather than a peripheral one.

Respondents ranked the following features for redesigned footwear using a 5-point Likert scale:

Table 2: Feature importance priorities

Feature	Mean Score	SD	Rank	Priority %
Heat resistance (up to 300°C)	4.67	0.58	1	33.2
Water resistance	4.23	0.71	2	15.1
Lightweight design	4.18	0.69	3	12.7
Slip resistance	4.15	0.73	4	11.8
Comfort and breathability	4.12	0.68	5	10.9
Shock absorption	4.08	0.75	6	8.7
Durability	3.95	0.81	7	4.8
Quick donning/doffing	3.87	0.79	8	2.8

The relatively narrow spread of mean scores across all eight features indicates a broadly consistent set of expectations among respondents, with thermal performance nonetheless standing out as the defining priority for next-generation protective footwear design.

Statistical Analysis Results

Chi-Square Analysis

To examine the relationship between reported footwear challenges and respondent agreement on the need for redesign, a chi-square test of association was conducted. The null hypothesis posited no significant association between the two variables, while the alternative hypothesis proposed a meaningful relationship. The analysis yielded a chi-square statistic of 28.47 with seven degrees of freedom, and a p-value of less than 0.001, leading to rejection of the null hypothesis at a high level of statistical significance.

Primary Hypothesis Testing:

- **H_0:** No association between current footwear challenges and redesign agreement;
- **H_1:** Significant association exists between challenges and redesign agreement.

Results:

i. Chi-Square Statistic: $\chi^2 = 28.47$;
ii. Degrees of Freedom: df = 7;
iii. p-value: $p < 0.001$;
iv. Effect Size (Cramér's V): 0.272 (medium effect).

Effect size was assessed using Cramér's V, which returned a value of 0.272, indicative of a medium practical effect. These results confirm a highly significant association between the footwear performance challenges experienced by operational personnel and their endorsement of redesign necessity, providing robust statistical support for the central research premise.

Conclusion: Highly significant association between footwear challenges and redesign necessity ($p < 0.001$).

Group Comparison Analysis

One-way ANOVA revealed statistically significant between-group differences across all three variables — heat resistance priority, comfort importance, and durability concerns — with moderate effect sizes observed in each case. Post-hoc Tukey HSD comparisons further indicated that senior firefighters prioritised heat resistance significantly more than junior personnel, reflecting greater accumulated exposure to high-temperature environments, while long-tenure professionals placed greater emphasis on durability, likely owing to heightened awareness of footwear degradation over extended service. These findings confirm that experience level meaningfully shapes feature prioritisation, underscoring the need for redesign approaches that address the differentiated requirements of personnel across career stages.

Table 3: Group comparison analysis

Variable	F-statistic	p-value	η²
Heat resistance priority	12.34	<0.001	0.089
Comfort importance	8.67	<0.001	0.064
Durability concerns	6.45	0.002	0.048

Post-hoc Analysis (Tukey HSD):

1) Senior firefighters prioritize heat resistance significantly more than junior staff ($p < 0.001$);
2) Experienced personnel (>15 years) emphasize durability more than newer staff ($p = 0.003$).

Interview Results Analysis

Quantitative Summary of Qualitative Responses

Analysis of the 75 firefighter interviews revealed consistent and pervasive dissatisfaction with current footwear across multiple operational dimensions. Weight and mobility restrictions emerged as the most widely reported concern, cited by nearly all respondents, closely followed by breathability and thermal comfort issues and inadequate heat protection, each reported by a substantial majority. Poor traction on wet surfaces and discomfort during extended operations were also prominently featured, with more than four in five respondents identifying these as significant challenges. Flexibility limitations and durability concerns were raised by approximately three-quarters of the sample, while difficulties with quick donning and doffing, foot fatigue and injury risk, and maintenance challenges, though reported by a somewhat smaller proportion, nonetheless reflect meaningful operational burdens. The convergence of these findings across a geographically and experientially diverse interview sample underscores the systemic nature of current footwear deficiencies, and lends strong qualitative support to the quantitative survey findings reported earlier.

Design Requirements Synthesis

Triangulating findings from both the survey and interview data, an evidence-based priority ranking of critical footwear requirements was established by combining quantitative priority ratings with qualitative reporting frequency. Enhanced heat resistance up to 300°C was confirmed as the foremost requirement, ranking first in the survey and among the highest in interview frequency, reflecting the thermal demands of operational firefighting environments. Improved breathability and comfort, and reduced weight and bulk, secured the second and third combined ranks respectively, with both features recording exceptionally high interview frequency despite comparatively modest survey priority scores, suggesting that these concerns are more acutely articulated through experiential accounts than formal rankings. Better water resistance and enhanced slip resistance occupied the fourth and fifth positions, each supported by strong evidence across both instruments. Improved flexibility, while absent from the formal survey rankings, featured prominently in interview data and was accordingly assigned the sixth combined rank. Better durability and ease of quick donning and doffing consistently occupied the lower end of the priority spectrum across both data sources, though they remained relevant considerations. The convergence of survey and interview evidence across these eight requirements provides a robust, empirically grounded foundation for the subsequent design specification and prototype development phases of this research.

Table 4: Critical Requirements (Evidence-Based Priority Ranking)

	Requirement	Survey Priority	Interview Frequency	Combined Rank
1.	Enhanced heat resistance (300°C)	1 (33.2%)	3 (89.3%)	1
2.	Improved breathability/comfort	5 (10.9%)	2 (92.0%)	2
3.	Reduced weight and bulk	3 (12.7%)	1 (94.7%)	3
4.	Better water resistance	2 (15.1%)	4 (85.3%)	4
5.	Enhanced slip resistance	4 (11.8%)	4 (85.3%)	5
6.	Improved flexibility	Not ranked	6 (77.3%)	6
7.	Better durability	7 (4.8%)	7 (73.3%)	7
8.	Quick donning/doffing	8 (2.8%)	8 (68.0%)	8

Comparison with Global Standards and Literature

Performance Gap Analysis

Comparative gap analysis between current Indian protective footwear and international standards [5] revealed statistically significant deficiencies across all four parameters. Heat resistance was the most critical, with Indian footwear frequently performing below the international minimum threshold ($p < 0.001$). Average boot weight exceeded the internationally preferred ceiling, representing a moderate but significant gap ($p = 0.023$). Flexibility showed a major shortfall, with current footwear achieving considerably less ankle range of motion than the stipulated minimum ($p < 0.001$). Water resistance performance was inconsistent relative to the IPX6 equivalent benchmark ($p = 0.012$) [12]. Collectively, these findings provide statistically grounded evidence of systemic performance inadequacy in existing Indian protective footwear, reinforcing the rationale for specification-driven prototype development.

Comparative Analysis of Existing Protective Footwear Designs & Proposed Footwear

A comparative analysis benchmarking the proposed designs against existing products covers: (i) current Indian IS 15298 market boots representing standard procurement, and (ii) two proposed prototypes — Design A and Design B. Data for the prototype designs are drawn from component qualification and assembled boot testing conducted at the collaborating BIS-approved laboratory, in accordance with conformity assessment procedures [13].

Table 5: Comparative performance analysis: current Indian market boots and proposed prototypes

Parameter	Current Indian IS 15298 Market Boots	Design A — Prototype 1	Design B — Prototype 2
Heat resistance — sole	300°C/1 min (IS 15298 minimum; often inconsistently achieved)	300°C/1 min ✓ (Nitrile Fire & Ice compound)	300°C/1 min ✓ (Nitrile Fire & Ice compound)
Breathability (MVTR at 38°C)	~128 g/m²/24h typical (IS 15298: not specified)	487 g/m²/24h (+280% vs Indian market; +21.8% vs 400 g/m²/24h threshold)	487 g/m²/24h (same Tex membrane)
Weight per pair	2.8–3.5 kg average	2.02 kg ✓ (target ≤2.2 kg)	2.31 kg (0.11 kg above 2.2 kg target; TPU panel trade-off)
Ankle ROM (% unshod)	60–70% typical	~83% ✓ (target ≥80%)	~73% (design trade-off accepted for industrial protection)
Slip resistance (CoF, wet tile)	≥0.28 (IS 15298 minimum; typically 0.28–0.33)	0.44 CoF (+57% above IS minimum)	0.44 CoF (+57% above IS minimum)
Emergency doffing time	No mechanism; >60 s	12.4 s (SD=1.3; n=3) ✓ — Protected Rapid-Release Closure System	23.7 s (triple closure; partial — no equivalent mechanism in current market)

Parameter	Current Indian IS 15298 Market Boots	Design A — Prototype 1	Design B — Prototype 2
Anthropometric fit (Indian foot)	European last standard — documented poor forefoot/arch fit in Indian populations [14]	UK size 8- Kanpur-evolved Indian last: wider forefoot, reduced medial arch height; confirmed by manufacturer design team	Same Indian last as Design A

Both prototypes were designed to deliver substantial performance improvements over current Indian market boots across all critical parameters. Design A was developed to meet weight, ankle flexibility, and emergency doffing targets, with breathability and slip resistance specifications significantly exceeding IS 15298 minimums, and the Protected Rapid-Release Closure System proposed to enable rapid doffing in under 15 seconds. Design B, incorporating an external TPU ankle panel for enhanced structural protection, was designed with acknowledged trade-offs in weight and ankle ROM. Both prototypes share identical thermal barrier specifications, breathability, slip resistance, and an Indian-last anthropometric construction.

DESIGN THINKING APPLICATION AND SOLUTION FRAMEWORK

Design thinking provides a structured yet iterative methodology for translating empirical user insights into functionally differentiated design solutions, integrating deep stakeholder engagement with evidence-based ideation and prototype validation [15, 16].

Empathize Phase: Comprehensive User Understanding

A mixed methods approach integrated survey data (n=385; Cronbach's α=0.89) and semi-structured interviews (n=75) to elucidate user needs and challenges with empirical rigor.

Primary User Personas (Evidence-Based)

Cluster analysis identified three distinct user personas — Urban Firefighter, Industrial Emergency Responder, and Rural/Wildland Firefighter — each exhibiting differentiated operational contexts and footwear priorities. These findings affirm that a single uniform footwear specification is inadequate to address the heterogeneous needs of India's disaster management workforce.

K-means clustering (k=3, silhouette score=0.72) delineated three personas.

Persona 1 – Urban Firefighter (60%, n=231): High-rise operations; needs lightweight, flexible, quick-don designs. Challenges: confined-space mobility, prolonged discomfort. Priorities: weight reduction (mean=4.82, SD=0.41), breathability.

Persona 2 – Industrial Emergency Responder (25%, n=96): Chemical/thermal hazards; needs protective, durable gear. Challenges: heat shielding, permeation risks. Priorities: heat resistance (mean=4.71, SD=0.52), chemical protection.

Persona 3 – Rural/Wildland Firefighter (15%, n=58): Extended terrain deployments; needs terrain-adaptable, resilient comfort. Challenges: traction, endurance. Priorities: slip resistance (mean=4.65, SD=0.48), durability.

Prototype Phase: Design Specification Development

Core Design & Material Selected

Material and component configurations were evaluated sequentially against four criteria, with progressive elimination employed until an optimal nine-component stack was identified. The primary criterion was thermal protection performance, requiring resistance to contact heat up to 300°C for three minutes at the outsole, an effective radiant heat barrier [17], and flame resistance with no continued burning. The second criterion concerned total assembled thickness, stipulating that the boot must fit on an Indian-specific last without excess bulk. Weight per pair constituted the third criterion at 2.5 kg or less per pair, with Carbon-Kevlar composites preferred over steel toecaps on account of a 61% weight saving. The fourth criterion addressed production feasibility, requiring fabricability within Indian manufacturing facilities using available skilled labour.

The final material architecture comprises a nine-component stack. The outer shell employs 2.2mm flame-retardant, water-resistant, full-grain chrome-tanned leather in rough-out orientation, tested in accordance with IS 2387 [18]. An aluminised para-aramid felt thermal barrier intercepts conductive and radiant heat between the outer shell and the membrane assembly, while localised Kevlar woven fabric patches bonded at high-stress upper zones provide cut resistance, puncture resistance, and thermal stability. The waterproofing and moisture management assembly spans three sub-components: a PBI/meta/para-aramid flame-resistant substrate; an expanded PTFE microporous membrane; and a hydrophilic polyurethane monolithic coating with thermally bonded seam sealing. The multi-density memory foam insole delivers fatigue reduction across operational shifts of twelve hours or more. The Nitrile rubber Fire and Ice outsole offers traction across -40°C to +300°C, SRC-rated slip resistance, and chemical and oil resistance. The Carbon-Kevlar composite midsole plate and toecap, rated at 400N and 200J/15kN respectively, provide puncture and impact protection at 61% less weight than steel equivalents.

Design A & Design B Prototypes

K-means cluster analysis identified three statistically distinct user personas. Persona 1, the Urban Structural Firefighter, representing the largest segment, prioritised rapid movement, quick donning and doffing, and minimal weight in high-rise operational contexts, directly informing Design A — a low-mid ankle boot with the Protected Rapid-Release Closure System and a target weight of 2.2 kg. Persona 2, the Wildland and Forest Firefighter, prioritised lower leg protection, ankle support on uneven terrain, and extended field durability, informing Design B — a tall shaft boot incorporating an external TPU ankle panel and triple-element closure system. Persona 3, the Industrial Emergency Responder, centred on chemical fire response, contaminated surface traction, and chemical permeation resistance; however, this persona was designated a scope exclusion as the requisite Class II all-rubber construction falls outside the Class I leather upper framework of this research. Accordingly, the present research considers Design A and Design B as the two prototype configurations taken forward for specification development, fabrication, and performance validation, with Design C excluded from the scope of this study.

Figure 3. Design A (Persona 1) & Design B (Persona 2)

Design Features

Design A is configured as a low-mid ankle boot with a shaft height of approximately 160mm, optimised for urban agility and stair navigation. Against a target weight of 2.3 kg per pair, the prototype achieved 1.90 kg per pair. The closure system employs a waterproof zipper concealed beneath a wide Velcro protective flap, forming the basis of the key design innovation — the Protected Rapid-Release Closure System — which enables emergency doffing in under 15 seconds through single-hand operation. Ankle range of motion is maximised at approximately 83% of unshod ROM [2], facilitating multi-storey movement. Design A achieved full IS 15298 (Part 2):2024 compliance [4].

Design B is configured as a tall shaft boot with a shaft height of approximately 265mm, designed to provide lower leg flame protection and mechanical debris resistance for wildland and terrain-based operational contexts. Against a target weight of 2.6 kg per pair, the prototype achieved 2.2 kg per pair. Ankle protection is enhanced through an externally moulded TPU panel at the lateral and medial malleolus zones. Ankle range of motion is approximately 73% of unshod ROM, representing a deliberate protection-mobility trade-off. Both designs share an identical nine-component material architecture, Indian-specific last geometry [14], Carbon-Kevlar composite toecap rated at 200J and 15kN, Nitrile rubber Fire and Ice outsole, ePTFE layer bicomponent membrane bootie, aluminised para-aramid and Kevlar patch reinforcement system, multi-density memory foam insole, integrated ankle protection, and cemented construction.

Test Phase: Validation Framework Development

Laboratory Performance Analysis — BIS-Approved Testing

Both prototype configurations were subjected to performance evaluation at a BIS-approved laboratory [13], with all specimens conditioned in accordance with BIS standard procedures prior to testing [4]. Design A was further validated against all ten mandatory IS 15298 (Part 2):2024 test parameters, achieving full compliance across every criterion. Outsole abrasion resistance was recorded at 139 mm³ against a maximum permissible threshold of 150 mm³, reflecting a 7.3% safety margin. Nail perforation resistance exceeded the minimum requirement of 1,100N by 11.9%, achieving 1,231N. Upper-to-sole bonding strength was recorded at 6.0 N/mm, surpassing the 4.0 N/mm minimum by 50%. Toecap impact resistance achieved 17.52mm internal clearance against the 14.00mm minimum (a margin of 25.1%), while toecap compression resistance recorded 17.46mm clearance, exceeding the threshold by 24.7%. Hot contact resistance at the sole passed fully at 300°C for three minutes with no melt or damage. Flame resistance was assessed across four separate components — upper leather, tongue, stitching thread, and quarter lining — with all four self-extinguishing upon removal of the flame source, confirming the integrity of the flame-retardant material system throughout the upper assembly.

Breathability, unspecified under IS 15298, was measured at 487 g/m²/24h for both prototypes [19], representing a 280% improvement over typical Indian market performance of approximately 128 g/m²/24h and exceeding the self-imposed threshold of 400 g/m²/24h by 21.8%. Design A achieved 2.02 kg per pair within the 2.2 kg target, while Design B recorded 2.31 kg as a documented trade-off attributable to the external TPU ankle panel. Slip resistance was identical across both prototypes at 0.44 CoF on wet tile [12], exceeding the IS 15298 minimum of 0.28 CoF by 57%. Emergency doffing time presented the most marked differentiation; Design A achieved 12.4 seconds via the Protected Rapid-Release Closure System, well within the 15-second target, while Design B recorded 23.7 seconds through its triple-element closure. Both prototypes were constructed on an Indian-specific anthropometric last derived from Kanpur-based practitioner measurements, incorporating a wider forefoot and reduced medial arch height relative to European standard lasts [14]. Collectively, the laboratory results confirm that both prototypes meet or exceed all applicable IS 15298 [4] mandatory thresholds, with conformity assessment procedures followed throughout [13].

Both prototype configurations — Design A and Design B — were subjected to performance evaluation at a BIS-approved laboratory, with all specimens conditioned in accordance with BIS standard procedures prior to testing. Design A was further validated against all ten mandatory IS 15298 (Part 2):2024 test parameters, achieving full compliance across every criterion. Outsole abrasion resistance was recorded at 139 mm³ against a maximum permissible threshold of 150 mm³, reflecting a 7.3% safety margin. Nail perforation resistance exceeded the minimum requirement of 1,100N by 11.9%, achieving 1,231N. Upper-to-sole bonding strength was recorded at 6.0 N/mm, surpassing the 4.0 N/mm minimum by 50%. Toecap impact resistance achieved 17.52mm internal clearance against the 14.00mm minimum, a margin of 25.1%, while toecap compression resistance recorded 17.46mm clearance against the same threshold, exceeding it by 24.7%. Hot contact resistance at the sole passed fully at 300°C for three minutes with no melt or damage. Flame resistance was assessed across four separate components — upper leather, tongue, stitching thread, and quarter lining — with all four self-extinguishing upon removal of the flame source and achieving full pass status, confirming the integrity of the flame-retardant material system throughout the upper assembly.

CONCLUSIONS

This study set out to address a critical and underexplored gap in Indian disaster management preparedness — the systematic inadequacy of protective footwear available to operational firefighting personnel. Through a rigorously designed mixed-methods framework encompassing a statistically validated survey of 385 professionals across six states, 75 in-depth interviews, comparative gap analysis against international standards, and evidence-driven prototype development, the research has generated a comprehensive, empirically grounded contribution to the field of protective footwear design in the Indian context.

The empirical findings unambiguously established that existing IS 15298-compliant market footwear falls short across multiple critical performance dimensions, with thermal protection, traction, weight, breathability, and anthropometric fit emerging as the most pressing deficiencies. The near-unanimous consensus among respondents regarding the necessity of redesign — supported by robust statistical evidence — underscores the urgency of the problem and validates the central premise of this research. Cluster analysis further revealed that India’s disaster management workforce is not a homogeneous user group, and that persona-differentiated design approaches are essential to adequately address the heterogeneous operational realities encountered across urban, wildland, and industrial deployment contexts.

The design thinking methodology adopted in this study enabled a structured translation of empirical user insights into two functionally differentiated prototype configurations. Design A, optimised for urban structural firefighting, achieved full IS 15298 (Part 2):2024 compliance across all ten mandatory test parameters, while simultaneously surpassing self-imposed performance targets for weight, breathability, slip resistance, ankle mobility, and emergency doffing time. The Protected Rapid-Release Closure System, for which a provisional patent application is in preparation, represents a novel design innovation with direct implications for operational safety. Design B, configured for wildland and terrain-intensive deployment, introduced deliberate and documented design trade-offs in favour of enhanced lower leg and ankle structural protection, while maintaining identical material architecture, thermal performance, and anthropometric fit as Design A.

Collectively, both prototypes demonstrate that it is feasible to develop IS 15298-compliant protective footwear that meaningfully surpasses current Indian market performance, incorporates Indian-specific anthropometric geometry, and addresses the operational priorities of end users — within the constraints of Indian manufacturing capabilities and supply chains. The research thereby contributes an evidence-based design specification, a validated nine-component material architecture, and a replicable methodology for user-centred protective equipment development applicable to the broader domain of occupational safety in India. Future research should address longitudinal field validation of both prototypes under operational conditions, wearability and fatigue studies over extended shifts, and the development of a Class II equivalent design to address the industrial emergency responder persona currently excluded from this study’s scope. Standardisation of breathability [19] and weight thresholds within IS 15298 [4] revisions is also recommended, given the empirical evidence presented here for their operational significance, and in alignment with national fire and emergency service guidelines [20].

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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 1/2026

Durability & Biodegradability: Is There a Contradiction?

Leather is known for its durability and performance. At the same time, it is being increasingly discussed in the context of biodegradability, circularity, and the bioeconomy.

At first glance, this may seem contradictory. How can a material designed to last also be biodegradable?

In this edition, developed together with Elisabetta Scaglia, Head of Environmental Services at **UNIC** – Concerie Italiane & Dietrich Tegtmeyer, Freelancer for Leather - we clarify common misconceptions and explain — in clear, evidence-based terms — how durability and biodegradability can coexist in leather.

Understanding the Basics

When it comes to leather - durability and biodegradability are **not opposites**. They operate on **different timeframes** and under **different conditions**.

Leather is produced from animal hides and skins, which are rich in collagen — a natural, bio-based protein structure. Through tanning, this collagen structure is cleaned from impurities and stabilised to ensure that bacteria can no longer use it as a food source, effectively stopping the rotting (putrefaction) process.

"Tanning is a process that converts a putrescible organic material into a stable material that resists decomposition caused by microorganisms, thereby increasing its durability"

Elisabetta Scaglia
Head of Environmental Services and Specifications, UNIC - Concerie Italiane.

This stabilisation does **not remove leather's natural origin** — it changes however, the chemical nature of the fibrous collagen structure so that it remains stable, flexible, and durable. Its use in consumer products allows them to be used for many years, reducing waste and avoiding premature disposal.

Tanning Chemistry vs Biodegradability:
Clearing the Confusion

One of the most widespread misconceptions is that tanning relies on so many chemicals that leather must then be "sealed" with a heavily plasticised finish — effectively turning leather into plastic. This is **incorrect**.

What Tanning Does:

● crosslinks collagen fibres by means of vegetable, mineral or synthetic tannins depending on the end-use (shoes, bags, gloves, furniture...)

● improves resistance to heat, moisture, and mechanical stress thanks to selected performance chemicals

● by definition when a surface coating or surface layer is applied to protect "leather" it cannot be thicker than 0,15mm, otherwise it has to be called "coated leather" and even in such a case the coating cannot be thicker than 1/3 of the total thickness of the material.

What Tanning Does NOT Do:

● it does not convert leather into a synthetic material

● it does not eliminate its natural, protein-based structure

It is true that after tanning, the surface of leather has to be protected to allow for longtime usage, and in many cases this is done with a synthetic layer. But this layer is very thin (< 150 µm). Therefore, normally **< 5% of the leather** in use is based on plastic.

As a result, despite the use of chemicals and protective layers, a sustainable leather today contains >90% natural based materials, allowing for far better biodegradability performance compared to many other so-called biobased alternatives.

Biodegradability in Practice

Biodegradable materials are substances capable of being broken down by microorganisms (bacteria, fungi, algae) and natural elements (sun, water, oxygen) into non-toxic, natural components like water, carbon dioxide, and biomass. As **Elisabetta Scaglia** explains:

"Biodegradation is the metabolic conversion of an organic material into simpler natural elements through the action of microorganisms under suitable environmental conditions."

A material with a higher proportion of bio-based chemistry may have a greater propensity for biodegradation but the two terms cannot be used interchangeably. More broadly, **all leather is biodegradable in principle**. However, for leather to biodegrade - like other natural materials (e.g. wood) - it needs the right conditions, which do not normally occur during use. The rate of biodegradation depends heavily on the environmental conditions and the presence of appropriate microorganisms.

What varies is the speed of degradation, depending on the tanning and finishing chemistry that is used.

Biodegradation does not occur while leather is being used, because the necessary conditions — sustained moisture, microbial activity, temperature, and oxygen — are typically absent. At the end of life, however, these conditions can enable biological breakdown. If leather as waste ends up in the environment, the degradation process starts for all its bio-based components.

Why This Matters for Sustainability and Circularity

Durability and biodegradability position leather as:

- A long-lasting material that prevents premature waste of its manufactures, promoting slow fashion.
- A bio-based product that can return to natural cycles at end of life depending on the chemistry used
- A source of inspiration for the development of a science-based circular economy

As EU policies increasingly focus on ecodesign & sustainability, circularity, and lifecycle thinking, it is essential that decisions are informed by facts, scientific evidence, and system-level analysis.

Durability and biodegradability in leather are not contradictions - they are complementary properties of this natural, bio-based material that just needs public support to develop its full potential.

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