Utilizing Gelatin Extracted From Fleshing Waste for Eco-Friendly Textile Applications

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ABSTRACT

This study investigates the use of gelatin derived from leather fleshing waste as a sustainable and eco-friendly resource to enhance the dye-fiber interaction. Gelatin was extracted using an alkaline pre-treatment followed by controlled thermal hydrolysis at temperatures ranging from 70–100°C.The extract was filtered to remove impurities and obtain a highly purified gelatin. The extracted gelatin was applied to bleached cotton fabric to enable salt-free and alkali-free reactive dyeing, thereby replacing conventional electrolytes and hazardous mordents commonly used in Cotton dyeing. Grafting gelatin onto cotton fibers significantly improved dye–fiber interactions by introducing new functional groups, under mildly acidic conditions, generated NH_3^+ cationic sites.

Chemical modification of the fabric was confirmed through FTIR spectroscopy, UV–Visible absorption analysis, and Colour-Eye K/S measurements. The gelatin-treated cotton fabric exhibited enhanced dye uptake, superior dye utilization, and improved coloration efficiency. UV–Vis analysis showed a 6.4% increase in dye exhaustion, while K/S values indicated a 7% improvement in colour fixation and 9.4% enhancement in overall dye utilization compared with conventional dyeing processes. Fastness testing exposed good performance, with ratings of 4/5 for washing, 5 for rubbing, and 4/5 for perspiration. Environmental assessment showed significant pollution load reduction, with BOD and COD decreasing by 61% and 63%, respectively, and TDS reduced by 22.5%, confirming the eco-efficiency of the gelatin-assisted, salt- and alkali-free dyeing process. In addition, the treatment improved the crease recovery angle to 120° due to crosslinking between amide and carboxylic groups. Overall, the results demonstrate that gelatin extracted from fleshing waste is a viable environmentally friendly substitute for synthetic chemicals in cotton dyeing process. This approach supports waste valorization, enhances fabric performance, and promotes sustainable and eco-conscious textile production.

Keywords: Green fleshing waste (gelatin), grafting, hydrolysis, salt-free dyeing and sustainability

Introduction

The textile industry is widely regarded as one of the most resource intensive and environmentally polluting industrial sectors, owing to the substantial consumption of water, energy, salts, alkalis, and synthetic chemicals during wet-processing operations such as dyeing, printing, and finishing. In particular, conventional reactive dyeing of cotton fabrics demands the use of large quantities of electrolytes commonly sodium chloride or sodium sulfate and alkaline agents to achieve effective dye fibre fixation. Consequently, textile effluents generated from these processes are resulting in high salinity, residual dyes, alkalis, chemical oxygen demand (COD), and total dissolved solids (TDS) in textile effluents [1,2].These effluents pose serious challenges to wastewater treatment and contribute to environmental degradation, especially in developing countries like Ethiopia where treatment infrastructure is limited [3].

Therefore, finding a way to improve dye utilization and avoid the use of inorganic salts and alkalis are important issues in the field of cotton coloration. At an academic level, many researchers and industries have investigated and addressed several findings and alternative technological advancements for the coloration of cotton with anionic dyes without the need for salt and alkali. Significant research efforts have concentrated on creating low-impact and environmentally friendly textile processing methods, such as salt-free dyeing, bio-based auxiliaries, and biodegradable finishing agents, in response to growing environmental restrictions and international sustainability programs [4, 5]. The use of natural and renewable polymers has drawn special interest among these strategies because of their non-toxicity, biodegradability, and capacity to include functional groups that can enhance dye-fiber interactions [6].

In addition to the challenges with textile sustainability, the leather processing sector produces a significant amount of solid waste, which makes up between 60 and 70 percent of the weight of raw hides. Collagen, a fibrous structural protein with great potential for value-added applications, is abundant in fleshing waste, which makes up a significant portion of this solid waste stream [7, 8]. Fleshing waste that is improperly disposed of causes serious environmental issues, such as soil contamination, odor production, and greenhouse gas emissions [9]. As a result, turning tannery waste into valuable resources is becoming recognized as a crucial tactic for implementing a circular economy and sustainable industrial development [10].

Collagen is partially hydrolyzed to produce gelatin, which has reactive functional groups including amino and carboxyl groups, hydrophilicity, and outstanding film-forming capacity. Gelatin is a viable option for green textile applications because of these potentials, which allow it to interact with textile fibers and dyes in an efficient manner [11, 12]. The use of gelatin and other biopolymers for textile finishing, coating, and surface modification has been recognized in earlier studies; however, little research has been done on gelatin that is specifically extracted from leather fleshing waste and its use in reactive dyeing of cotton fabrics without the use of salt or alkali [13, 14].

In this regard, the present study aims to utilize gelatin that derived from collagen-rich fleshing waste as a sustainable substitute for conventional dyeing auxiliaries. Gelatin is grafted onto cotton fibers to create new cationic sites that improve dye-fiber interactions under mild conditions and reducing the need for hazardous chemicals. In addition to enhancing textile performance, this strategy helps reduce pollution, value waste, and promote sustainable textile production.

Materials and Methods

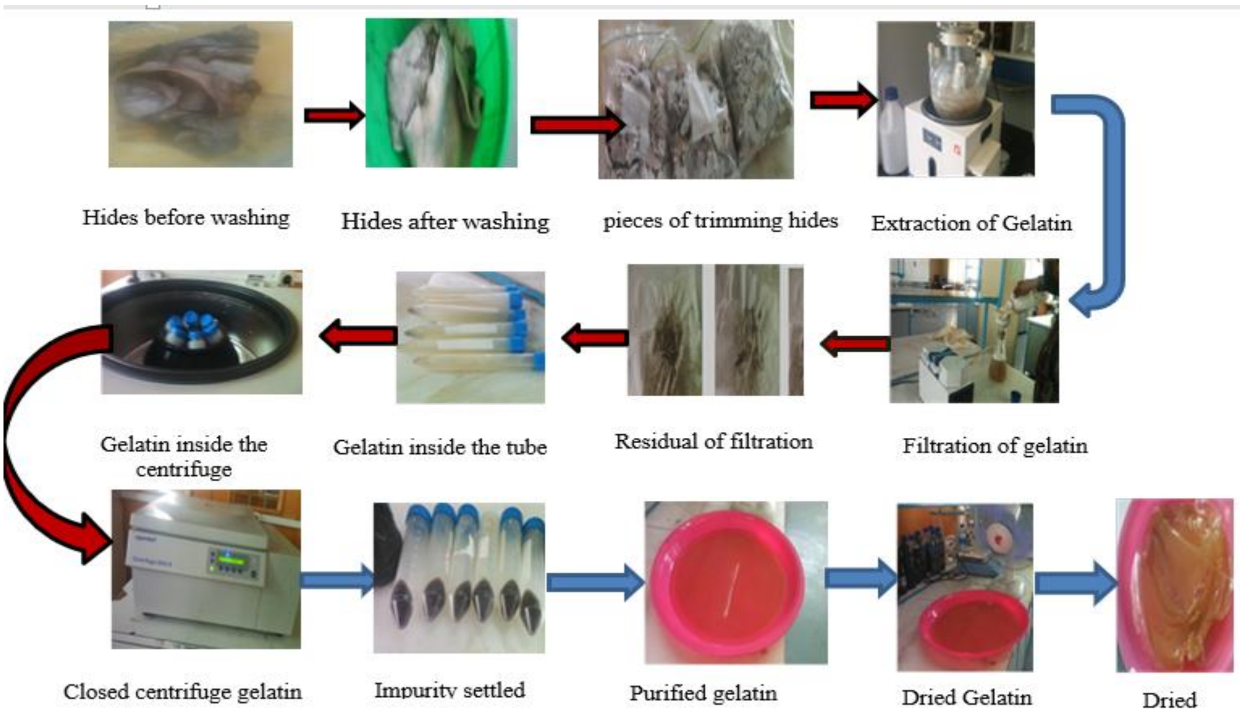
Materials

The materials and chemicals used in this study included green fleshing waste collected from local tanneries, which served as the primary raw material for gelatin extraction. Bleached 100% cotton fabric was used as the textile substrate for dyeing process. A monochlorotriazine (MCT) reactive dye, suitable for cotton dyeing, was selected as the colouring agent. Analytical and industrial grade chemicals used during alkaline pre-treatment and dyeing processes such as sodium chloride (NaCl) as an electrolyte, sodium carbonate (Na_2CO_3) as an alkali, a sequestering agent to control metal ions, a wetting agent to enhance fabric wettability, acetic acid for pH neutralization, and soap for post-dyeing washing and soaping treatments.

2.2. Extraction of Gelatin from Fleshing Waste

The method of extraction of gelatin from raw hide trimming used in this study was alkaline treatment-thermal hydrolysis techniques [19] that does not need a any chemicals that can affect the environment. The chemicals that need for pre-treatment before extraction also eco-friendly to the environment. The main steps followed during the extraction of gelatin from hide trimming and fleshing waste are presented in the following Figure 1, and the steps are explained below. The animal hide trimming and fleshing waste were collected from a nearby tannery in Addis Ababa, Ethiopia. After collection, it was extensively cleaned with distilled water to get rid of any extraneous material and contaminants that had stuck to the hide's surface [16]. Subsequently, the hides were immersed in 1000 milliliters of water containing 0.3% (w/v) degreasers and 1% (w/v) sodium chloride for two hours at 30oC to eliminate the fat components. The skins were once again cleaned with water for 30 minutes at 40oC, and drying was performed using an oven-dry machine. The washed and dried hide skin trim was also chopped and grinded. After being chopped into tiny pieces, the hides were once again cleaned with water under high pressure. Then, the chopped hides were pre-treated for 24 hours in 100 cc of 0.4% (w/v) sodium hydroxide. Afterward, the alkali-treated hide was neutralized using HCl acid, and the gelatin was extracted via a thermal hydrolysis process using distilled water at a material liquor ratio of 1:5 (g/ml) at optimal temperatures (90^{O}C) for optimal durations (6 hours), resulting in an optimal yield efficiency of 92.4%.To create ultra-pure gelatin, the extracted gelatin was first filtered through plain cotton fabric to remove larger, undesirable particles that were naturally present in the hides. As shown in the fig1. the filtration was carried out by insert the gelatin contain tube inside the centrifuge and adjust the temperature at 30^{o}C and rotate the tube inside the centrifuge for 10 minutes at 900 rpm and finally the unwanted impurity settled at the bottom of the tube and then it has distillated the purify gelatin carefully

After distilled the pure solution drying of the gelatin and evaporate of water were carried out by using ventilator at conditioned room for three days at room temperature. Gelatin is not drying by sun because it melts easily.



Physicochemical Properties of Gelatin

Fourier Transform Infra-Red (FTIR)

The Fourier transform infrared (FTIR) spectra were collected in total reflectance mode with FTIR 4000. The FTIR test was performed on gelatin powder. The investigated wavenumber range was 4000–500 cm-1, and the resolution was 2 cm-1, with 64 scans performed on each sample. The spectra were acquired by absorbance.

Thermal Properties

The thermal degradation of the developed gelatin can be detected with differential Thermogravimetric analysis (TGA 4000) These machines were used to determine how much energy the gelatin sample was absorbing or releasing was carried out on a at a heating rate of 100C/min in a temperature range of 25 to 600 ^{o}C.

Percentage Yield of Extracted Gelatin

The yield of the gelatin extraction depends on the extraction temperature and extraction time. Gelatin was extracted from the collagen at various temperatures of 70°C, 80°C, 90°C and 100°C, with extraction times of 120 min, 240 min, 360 min, and 480 min, while maintaining constant conditions for other variables. The effects of the extraction time and extraction temperature on the gelatin yield were analysed using a two-way ANOVA. The extracted gelatin yield was calculated as a percentage by using the following equation:

Yield (%) = (W2/W1)*100 -------- (2)

Where W2 is the weight of the extracted gelatin and W1 represents the initial weight of the hide.

Application of Gelatin on Cotton Fabric

Gelatin was grafted onto the cotton fabric using a pad–dry–cure technique as shown figure 2 under controlled conditions to impart cationic functionality to the fiber surface.

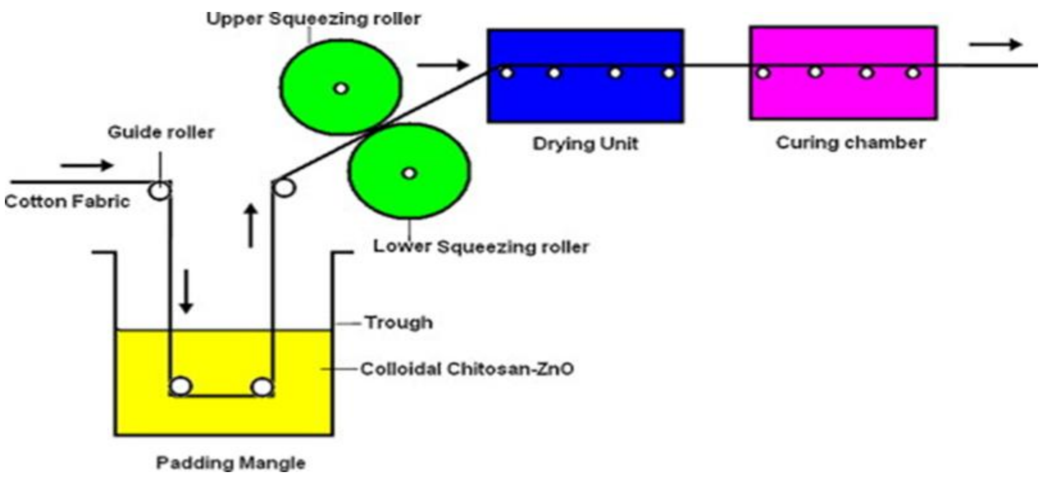


Figure 2: Treatment process of cotton fabric with hydrolyzed gelatin

The well-prepared bleached cotton fabric was padded with the optimum concentration of 20 g/l of extracted gelatin using laboratory padding mangle machine) at 80% wet pickup. The treated fabric was then subjected to drying at 100oC for 4 minutes in a hot air oven and further cured at a low temperature of 140oc for 4 minutes. The cat ionized samples were neutralized with a diluted acetic acid solution, rinsed with water, and dried at room temperature

Dyeing Mechanism of treated fabric

Both gelatin-treated and untreated cotton fabrics were dyed with reactive dyes under same processing conditions to enable a direct and unbiased comparison of dyeing performance. For control purposes, Conventional reactive dyeing using the standard addition of electrolyte (salt) and alkali was applied to untreated cotton fabric. This conventional method served as a benchmark to evaluate the effectiveness of the gelatin-based cat ionization treatment. The potential of gelatin-treated cotton for salt and alkali free reactive dyeing was systematically evaluated through comparative evaluations of dye uptake, fixing efficiency, color strength, and overall dyeing performance.

Dyed Fabric Characterization

Color Strength (K/S)

The reflectance of the dyed cotton fabric was measured by using a computer color matching system X 4000spectrophotometer under illuminant D65 using a 10° standard observer at the maximum dye absorption and then the color strength of the dye was calculated by the following kubelka Munk question.

K/S=(1-R)2/2R x100…………………………… (1)

Where R is the reflectance, K is absorbance and S is the scattering.

Exhaustion percentage (%E)

The optical density of the dye solution before and after the dyeing process was measured by using UV/ VIS spectrophotometer and then the dye bath exhaustion percentage were calculated by the following formula(6).

%E = ((A0-A1))/A1 x100………………………. (2)

Where Ao and A1 are the absorbencies at a maximum wavelength of the dye originally in the dye bath and residual dye after the dyeing process respectively.

Fixation of the Dye

To determine the fixation of the dye, the maximum k/s value of the dyed fabric was measured at a certain wavelength by using color eye 3100 before and after soaping.

%F = (K/S)b/((K/s)a) x 100……………………. (3)

Where K/S is the color yield with values before soaping (b) and after soaping.

Dye Utilization percentage(%T)

The total dye utilization percentage (%T) was calculated by using the following equation from the result of exhaustion &fixation percentage.

%T= (%E*%F)/ (100) ……………………… (4)

Colour fastness

The fastness properties of dyed samples were tested according to ISO standard methods. To examine the performance of the reactive dyed cotton fabric, the colorfastness to washing with white fabrics, colorfastness to perspiration, and rubbing tests were carried out according to ISO-X12(1987), ISO 105-E041997 C2S, and ISO 105-X12, respectively (20).

The impact of the cat ionized process was identified by the fastness results.

Crease recovery angle (CRA)

The crease recovery angle (CRA) of the dyed cotton fabric measured using crease recovery tester according to AATCC Test Methods 66. The method of the crease recovery angle of the treated fabric is prepared a sample with a sample size of 40mm*15mm and apply 1kg load for 5minuets. After removal of weight smoothly from the specimen, using tweezers insert the specimen in to instrument circular specimen holder and adjust the instrument to keep free hanging of the specimen in alignment vertically. Read and record the recovery angle from the circular scale 5 min after inserting a specimen in to a clamp. The result indicates that the CA treated fabric shows more Crease Resistance Angle increase as the concentration of the cross linking increase.

The dry crease recovery of durable press finished treated fabric analyzed in comparison with un treated bleached fabric. Therefore the percentage increment of DCRA calculated by the following formula.

%DCRA increase = DCRA of finished fabric – DCRA of untreated bleached fabric * 100……….. (4)

Determination of Tear Strength

The tear strength was tested according to the ASTM D2261-13standard method [21].Tear strength is the capacity of a material to withstand the tearing force required to propagate a tear after its initiation. The test specimen was cut according to the standard template size, and the required dimensions are specified in relevant test standards. Tearing strength was tested in the warp and weft directions using a digital tear tester with a C-type load. An initial cut of about 1 cm in length was made part way down the center of a strip, and then the two tails thus formed are pulled apart so that a tear proceeds through the uncut portion of the fabric. The force used to tear the fabric was measured and recorded.

Determination of Tensile Strength

The tensile strength of the fabric sample was determined by using the ASTM D5035-95 standard test method [22]. A fabric sample measuring 100 mm by 150 mm was prepared for both the warp and weft direction tests separately. The Universal Strength Tester was used to measure the tensile strength of the fabric in the warp and weft ways. The gauge length between the two jaws was adjusted to 75 mm.

Results and Discussion

The structural change in the cat ionized fabric was confirmed with different methods. The formation of amide groups determined the confirmation of the cationization of gelatin was determined with FTIR analysis and determined the color yield of the dyed fabric with Colour Eye 3100.

FT-IR R Analysis

The FTIR used to study the formation of an amide group on the treated fabric with gelatin

FTIR spectra showed characteristic amide and carboxylic peaks, confirming successful grafting of gelatin onto cotton fibers. These functional groups facilitated improved dye–fiber bonding.

FTIR analysis confirmed the successful chemical modification of cotton fabric by gelatin treatment using the pad–dry–cure method. The broad absorption band around 3420 cm^{-1} corresponds to the stretching vibrations of –OH and –NH groups, indicating interaction between cellulose and gelatin. The peaks at 2927 cm^{-1} and 1639 cm^{-1} are assigned to C–H

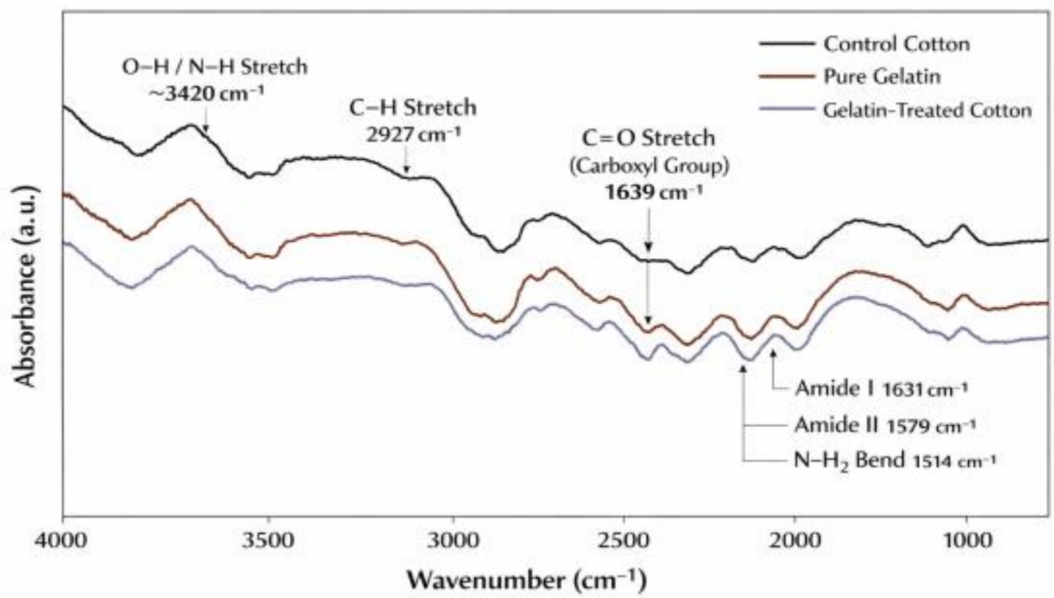


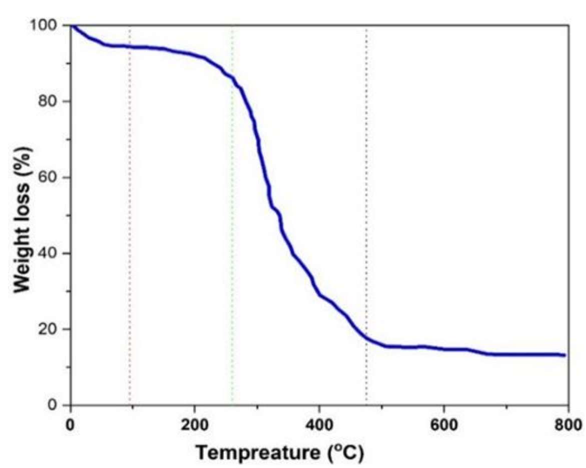
Figure 2: FTIR result of treated and un-treated cotton

stretching and C=O stretching of carboxyl groups, respectively, confirming the presence of gelatin-derived functionalities on the cotton surface. Pure gelatin exhibited characteristic amide I and amide II bands at 1631 cm^{-1} and 1579 cm^{-1}, along with an $–NH_2$-related band at 1514 cm^{-1}. The appearance of these amide and amine bands in the treated cotton fabric provides clear evidence of successful gelatin grafting and chemical interaction with the cellulose matrix.

TGA Thermal Properties of Gelatin

The thermal properties of the extracted gelatin is displayed in Figure 3.

From Figure 3, it can be shown that the Thermogravimetric analyses were conducted in the range of room temperature to 800◦C to estimate the thermal stability of the developed gelatin at control state. The TGA thermogram in Figure 3 shows a profile of weight loss with increasing temperature that can be divided into two separate regions. First, a slight degradation step with onset at around 95◦C, this first stage leads to a weight variation of around - 6.5%, due to loss of absorbed water. Second, a much more pronounced decline in mass close to 260oC, carrying a 14% weight reduction. In addition, at 47.5oC there was a degradation occurs and 82% weight loss. This stage corresponds to the degradation of the low molecular weight protein fraction, as well as structurally bound water.



Effect of Extraction Temperature on Gelatin Yield

Extraction of gelatin from collagen was carried out at 70℃, 80℃ 90℃ and 100 ℃ by keeping other factors constant. From this investigation it was observed that, the optimized extraction conditions were 90℃ extraction temperature &6hrs extraction time. At this optimized extraction conditions higher percentage yield of gelatin was obtained.

The extracted gelatin has the following yield percentage by different extraction conditions. As the result shows the highest yield of 92.4% was obtained at 90oc for 6 hours. When the temperature rises beyond 90oc for 8 hours the lower yield could be obtained due to the loss of extracted gelatin due to ultra-hydrolysis of the collagen.

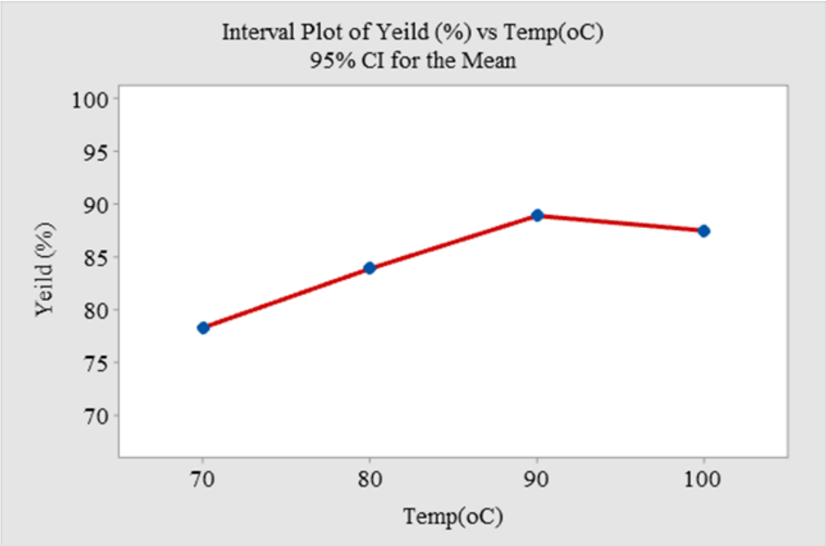


Figure4: Yield (%) vs Temp (OC)

Effect of Extraction Time on Gelatin Yield

Extraction of gelatin from collagen was carried out at 2hrs, 4hrs, 6hrs and 8hrs by keeping other factors constant. As the result shows the highest yield of 92.4% was obtained at 6 hours.

Dye Uptake and Colour Strength

The CIE LAB color space describes color using L*, a* and b* where L* indicates lightness, a* represents red–green, and b* represents yellow–blue. The cat ionized fabric showed a lower L* value, indicating a darker shade, while higher a* values confirmed more dye exhaustion due to the presence of amide groups introduced onto the cotton fabric.

Table 1: Colour Eye3100 Result forD65 standard 10^{o}

Colour factors	Bleached fabric	Conventional	Cat-ionized
L*	89	47.75	45.90
a*	0.45	53.46	54.38
b*	1.10	-3.37	-2.54

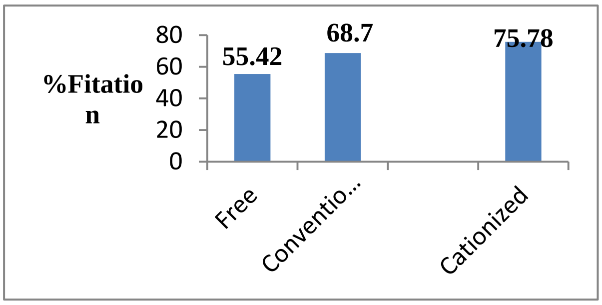


Figure5: Effect of treatment on fixation percentage

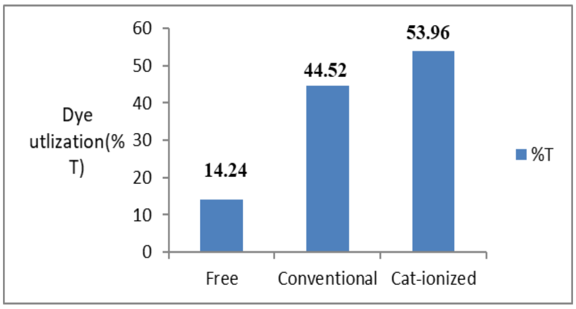


Figure 6: Effect of treatment on dye utilization

As shown on the above fig 5 gelatin-treated cotton fabrics exhibited a 6.4% increase in dye exhaustion, indicating more efficient transfer of dye molecules from the dye bath to the fibre. This enhanced exhaustion is attributed to the presence of amide functional groups introduced by gelatin treatment, which promote stronger interactions between the anionic dye molecules and the modified cotton surface. Fig 8 shows 7% improvement in colour fixation, as evidenced by higher K/S values before and after soaping, demonstrating that a greater proportion of the exhausted dye was effectively fixed within the fibre structure. As a combined result of improved exhaustion and fixation results dye utilization increased by 9.4% as compared to conventional dyeing. These improvements lead to deeper and more uniform coloration, reduced dye loss in effluent, and enhanced economic and environmental sustainability of the dyeing process.

1.1. Fastness Properties

Gelatin-treated cotton fabrics confirmed good fastness performance, with washing fastness of 4/5, rubbing fastness of 5, and perspiration fastness of 4/5, meeting acceptable textile standards. The gelatin treated cotton fabrics exhibited satisfactory color fastness properties, signifying their durability and practical applicability. Specifically, the treated fabrics achieved a washing fastness rating of 4–5, indicating minimal color loss or staining during laundering. Rubbing fastness was rated 5, reflecting excellent resistance to color transfer under both dry and wet conditions. Additionally, perspiration fastness was measured at 4–5, confirming the stability of the dye under acidic and alkaline conditions simulating human sweat. These results indicate that the gelatin modification not only enhances dye uptake but also maintains the dyed fabric's performance within acceptable textile industry standards.

Table 2: Fastness property of the dyed fabric

Fastness property		Un cat-ionized fabric Dyeing Condition		Cat ionized fabric Dyeing Condition	
		Alkali	Acidic	Alkali	Acidic
Washing fastness		5	-	3	4/5
Rubbing Fastness	Dry	5	-	4	5
	Wet	4/5	-	¾	4/5
Perspiration fastness		4/5		¾	4/5

Physical Properties of the Dyed Fabric

One common concern during the dyeing of cotton fabrics with reactive dyes under acidic conditions is the potential negative impact on the fabric's physical properties. Cotton fibers are naturally sensitive to strong acids, which can lead to fiber weakening, reduced tensile strength, or changes in handle and texture. However, in this study, dyeing with reactive dyes under mildly acidic conditions does not cause significant deterioration of fabric physical properties. The controlled pH and short processing duration minimize cellulose degradation, preserving fabric strength and durability. Compared to conventional salt-assisted dyeing methods, the acidic dyeing approach exerts a less adverse impact on fabric properties, while also reducing chemical load. Overall, mild acidic reactive dyeing is a safe and environmentally favorable alternative to conventional dyeing processes.

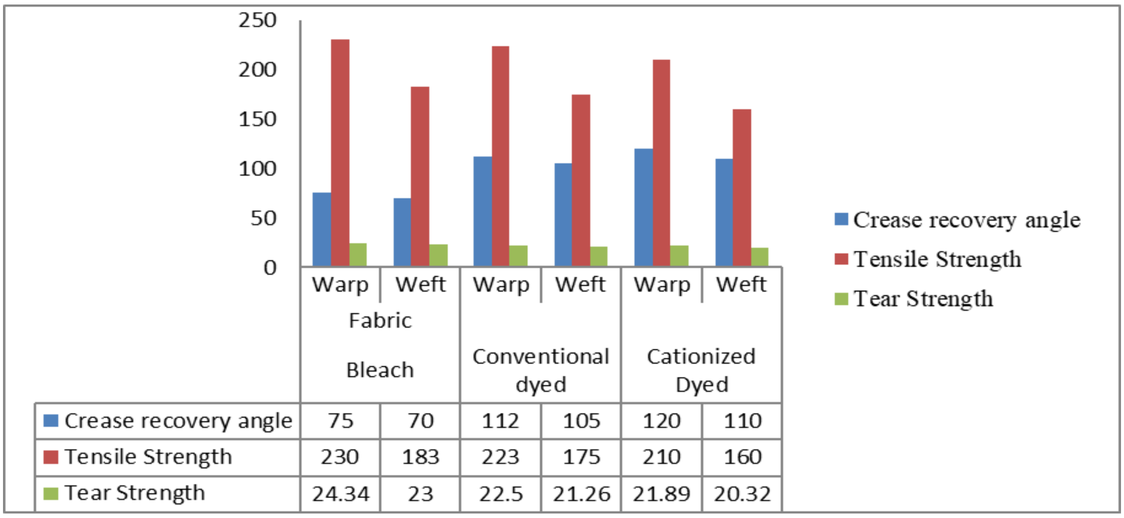


Figure7: Effect of cat ionization on physical properties of dyed fabric

Environmental and Sustainability Implications

The characteristics of the wastewater before and after treatment were evaluated using key pollution indicators, such as chemical oxygen demand (COD), biological oxygen demand (BOD_5), and total dissolved solids (TDS). The proposed process eliminates the need for salts and alkalis in reactive dyeing, significantly reducing wastewater pollution. Moreover, valorization of leather fleshing waste contributes to waste minimization and supports circular economy practices in textile and leather industries.

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Table3: Waste treatment Analysis

Sample	Conventional	Treated	Removal Efficiency (%)
BOD(mg/l or ppm)	267.00 mg/l	104 mg/l	61%
COD(mg/l or ppm)	576.4mg/l	206.2mg/l,	63%
TDS(mg/l or ppm)	864.6 mg/l	670.5 mg/l	22.5%

The untreated wastewater showed high pollution levels, with BOD_5 (267.00 mg/l), COD (576.4mg/l), and TDS (864.6 mg/l), indicating substantial organic contamination and dissolved salts from textile and industrial processes. After treatment, BOD_5 and COD were significantly reduced to 104 mg/l and 206.2mg/l, achieving removal efficiencies of about 61% and 63%, respectively, and reflecting effective removal of biodegradable and oxidizable organic matter. However, total dissolved solids (TDS) removal was limited, decreasing only to 670.5 mg/L (22.5% reduction), as conventional dyeing effluent treatments are generally ineffective at removing dissolved inorganic salts without the application of advanced separation technologies. This outcome is expected, since the gelatin-assisted approach is not designed as a wastewater purification process but rather as a fiber surface modification strategy aimed at enhancing dye–fiber interactions. Grafting gelatin onto cotton introduces amine-containing functional groups that generate cationic sites under mildly acidic conditions, thereby promoting stronger electrostatic attraction and covalent bonding with reactive dyes. This enhanced dye fixation substantially suppresses dye hydrolysis, which is a major source of unfixed and environmentally persistent dye species in conventional dyeing systems. Consequently, the observed environmental improvements particularly the significant reductions in COD and BOD stem from source-level pollution prevention through improved dye utilization and minimized discharge of hydrolyzed dyes, rather than from direct removal of dissolved pollutants from the effluent.

Conclusion

This study confirms that gelatin extracted from leather fleshing waste is an effective, green, and sustainable alternative to conventional synthetic dyeing of cotton fabric. The use of gelatin significantly enhanced dye–fiber interactions, resulting in higher dye uptake and improved colour strength in treated cotton fabrics. Furthermore, the gelatin treated fabrics exhibited satisfactory to good fastness properties to washing, rubbing, and perspiration, demonstrating stable dye fixation and durable performance. This waste-derived, bio-based approach not only improves dyeing efficiency but also aligns with circular economy and sustainable manufacturing principles by valorizing leather industry waste. In general, the findings highlight the strong potential of gelatin extracted from fleshing waste as an environmentally friendly and industrially viable solution for advancing cleaner, more responsible textile dyeing processes.

Recommendation

The results of this study show that gelatin extracted from leather fleshing waste is a sustainable substitute for traditional synthetic dyeing auxiliaries in the colouration of cotton fabrics. Its use promotes waste valorization and the concepts of the circular economy while improving dye uptake, colour strength and fastness performance.

Based on the findings of this study, the researcher recommended for:-

- ✓ Textile industries to integrate waste-derived gelatin into dyeing operations to improve process efficiency and reduce reliance on synthetic chemicals.
- ✓ Leather tanneries to adopt gelatin recovery from fleshing waste as a value-added waste management strategy, minimizing environmental burden while generating usable bio-based materials.
- ✓ Academicals and researchers should focus on process optimization, multi-substrate and multi-dye applicability, durability, biodegradability, and life-cycle assessment to strengthen industrial scalability.
- ✓ Policy makers and other concerned bodies are urged to support pilot-scale implementation, techno-economic assessment, and regulatory frameworks that facilitate the adoption of bio-based auxiliaries in textile and leather sectors

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