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Oil extracted from spent coffee grounds as a fatliquor in leather tanning

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Abstract

This study explores the potential of using spent coffee grounds (SCGs) oil as an eco-friendly alternative to traditional fish-oil in leather fatliquoring. SCGs oil was extracted and converted into an aqueous grease then used at various concentrations (5%, 10%, 15%, 20%) for application to sheep wet-blues. A fish-oil group served as the control. The extracted SCGs oil (12.12% yield) exhibited a promising fatty acid profile (47% saturated, 52.8% unsaturated), suitable for leather fatliquoring. Analysis of the resulting leathers revealed comparable quality between SCGs and fish-oil at equivalent concentrations. Notably, SCGs leathers displayed a more homogeneous structure, potentially enhancing physical properties. The findings suggest that SCGs fatliquor offers good filling and mechanical properties, with an optimal concentration around 10% for maximizing overall leather quality. While chemical properties showed minimal differences between SCGs and fish-oil leathers, SCGs fatliquor emerged as a viable and sustainable alternative. This approach promotes economic and environmental benefits by utilizing waste materials in the leather tanning process.

Keywords: Characterization; Extraction; Tanning; Preparing; Physical properties

1. Introduction

Leather tanning, one of the oldest industries in history, involves the conversion of animal hides into usable leather for various leather products. The tanning process comprises three main stages: pre-tanning, tanning, and post-tanning or finishing [1]. During the post-tanning stage, a step called fatliquoring is performed to compensate for the loss of fatty materials from the skins/hides that occurs during the initial stage before tanning [2]. Fatliquoring is a vital part of leather treatment, contributing to the suppleness, waterproofing, and improved appearance of the leather [3].

The primary components used in leather fatliquoring products are fats, oils, and waxes [4,5]. Fatliquors are chemical additives incorporated into the tanning process to enhance the softness, flexibility, and durability of leather, while also preventing damage and maintaining a smooth texture [6,7]. Various types of fatliquors are used in the leather industry, including animal oils and vegetable oils such as neat's-foot oil, fish-oil, olive oil, and castor oil [4]. These oils contain unsaturated fatty acids (UFAs) that can be converted into emulsifying fat agents, which are employed in the tanning process to modify the properties of leather [8].

To enhance sustainability and maximize economic and environmental benefits, it is crucial to repurpose waste into valuable materials. Coffee, the world's second most traded commodity after oil, is also the second most consumed beverage globally. However, only about 30% of a coffee bean's mass is used for brewing, resulting in a significant amount of spent coffee grounds (SCGs) that are often discarded [9, 10]. This disposal practice contributes to environmental issues, with substantial quantities being discarded daily [11, 12]. Fortunately, SCGs can be recycled and repurposed in various ways, such as using them as fertilizer, a feedstock for microalgae-based biofuels, a raw material for new products [13,14], or an additive in cement mortar to improve its properties [15]. By implementing these strategies, the negative environmental impact of SCGs can be mitigated [16].

SCGs contain approximately 10-13% oil, rich in unsaturated fatty acids (UFAs) [17-19]. While various methods exist for oil extraction, including Soxhlet and supercritical fluid extraction, these often require dried materials and can be time-consuming and energy-intensive [20]. Two-phase solvent extraction and ultrasound-assisted solvent extraction are promising alternatives, especially for materials with high moisture content. While different extraction methods may influence yield, their impact on fatty acid composition remains unclear [21,22]. This study focuses on traditional Soxhlet extraction to assess the suitability of SCGs oil for leather fatlquoring. Further research may need to explore the efficiency of other extraction methods

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in producing fat for leather tanning from SCGs.

On the other hand, the conversion of UFAs-containing oils into greases through the sulfonation process is feasible. Sulfonation involves treating the oil with sulfur trioxide gas, followed by the addition of a neutralizing agent to produce a sulfonate surfactant [23]. These sulfonate surfactants can be utilized as greases due to their ability to reduce friction and wear [6,24]. However, it is important to note that not all UFAs-containing oils are suitable for sulfonation, as the properties of the resulting sulfonated product can vary depending on the composition of UFAs present in the oil used.

In a previous study, SCGs was explored for its potential in leather tanning by extracting tannins for use in the tanning process [25]. This current research, however, focuses on a novel approach that leverages the oil content of SCGs as a fatliquoring agent in the finishing stage of leather processing, expanding the potential applications of coffee waste in the leather tanning industry. The objective of this study is to extract oils from SCGs and convert them into a fatliquor that can be used for fatliquoring tanned leathers, while also determining its impact on the physical and chemical properties of the finished leathers.

2. Experimental

Materials

The study utilized 20 kilograms of SCGs obtained from local coffee shops. Eight cow wet-blues were sourced from El-Shafie Son's tannery in Alexandria, Egypt. The wet-blues were all similar in thickness and size, free of any visible defects, and classified as first grade. Laboratory-grade chemicals, including sulfuric acid, sodium hydroxide, sodium chloride, hexane, and petroleum ether, were procured from El-Gomhouria Company for Chemicals in Egypt.

Methods:

The experimental design:

The study was divided into four main parts as follows:

- Spent coffee grounds preparation:

Twenty kilograms (20 kg) of used SCGs were initially air-dried in a shaded area for three days. Subsequently, they underwent further drying in a dedicated oven at 105°C for ten hours.

- Oil extraction process:

The oil extraction procedure employed a solvent-based method (hexane) similar to the one described by Oliveira *et al.* [26] with slight modifications. The dried SCGs were mixed with hexane in a closed container at a 1:5 kg:L ratio. The mixture was maintained at room temperature (22 ± 2 °C) with continuous stirring every 30 minutes for a total duration of 8 hours. Finally, the extraction mixture was distilled and dried following the method outlined by Jin *et al.* [27] to isolate the coffee oil. The final step involved separating the oil from the solvent using a rotary vacuum evaporator.

- Fatliquor emulsion preparation:

The fatliquor emulsion preparation was adapted from the method described by Santos and Gutterres [28] with some modifications. Sulfuric acid (98%) was gradually added dropwise to the SCGs oil at a ratio of 30% (w/w). To maintain control, the addition occurred under slow stirring while keeping the temperature below 30°C. Following the addition, the mixture underwent a sulfation process for 180 minutes. Afterward, the mixture was washed with water at room temperature to remove unreacted acid. Finally, the solution was neutralized to a pH of 6-7 using a 20% aqueous solution of sodium hydroxide with continuous stirring for 30 minutes.

- Leather processing:

Eight cow wet-blues were designated for post-tanning treatments according to the recipe outlined in Table 1. The wet-blues underwent fatliquoring with four varying concentrations of the fatliquors: 5%, 10%, 15%, and 20%. Both fatliquors of prepared SCGs oil and commercial fish-oil were utilized as fatliquoring agents across these concentrations. Notably, fish-oil fatliquor served as the control, representing the traditional fatliquor commonly employed in tanneries. Consequently, each group consisted of a single wet-blue hide. After finishing, tanned leather quality was tested physically and chemically for all tanned leathers.

Properties measured during the experiment:

- Characteristics of SCGs:

Twenty grams sample of SCGs were taken to determine moisture, ash, fat contents and density according to AOAC [29].

- Characteristics of extracted SCGs oil:

Iodine value:

According to the method (Cd 1c-85) of AOCS [30] the iodine value is calculated as the sum of the percentage of each UFA in the sample, multiplied by a number of double bonds for that fatty acid (based on its level of unsaturation and its molecular weight). The following equation (1) was used:

$$\text{Iodine value} = \Sigma\,(254 \times A_i \times D)\,/MW \quad (1)$$

Where: A_i is fatty acid percentage, D is a number of double bonds and MW is the molecular weight.

Table 1. Post-tanning recipe used during the experiment.

Process	%	Chemical	Time	℃	pH	Operation
Re-tanning	150	H_2O				
	0.1	FORMIC	60		3.8	Drain
	200	H_2O		35		
	0.8	BLACK NX	10			
	2	LZR FRH				
	2	CROME 33	60			
Fixation	1	SOD. FORMATE	60			
Neutralization	1	LZR NTS	10			
	1	$NaHCO_3$	90		5.5	Drain and wash
Dyeing	80	H_2O				
	3	POLO RG	30			
	0.5	LZR LNO	5			
	3	LZR FRH				
	3	LZR MRS				
	3	LZR DRS				
	1.5	MIMOSA				
	2	LZR SW				
	2	BLACK PEN				
	0.5	BLACK AF 135	90			Over night
Fatliquoring	100	H_2O		50		Fatliquor percentage according to experimental group
	X	Fatliquor	120			
Fixation	2.5	Formic	60			Drain and wash
		Vacuum 65/ 3 MIN.				

* All wet-blues were shaved mechanically before post-tanning by shaving machine to adjust leather thickness to 0.9mm

Saponification value:

According to the method (Cd 3a-94) of AOCS [31] saponification value is calculated upon the molecular weight of all fatty acid present in sample as explained in the following equation (2):

$$\text{Saponification Value (SV)} = \Sigma \frac{P/_{100} \times 56.11 \times 1000}{MW} \quad (2)$$

Where: P is a percentage of fatty acid and MW is the molecular weight.

Acid value:

According to AOAC [32] the acid value of SCGs oil was determined as follows: 2 gm of oil were dissolved in 30 ml of neutral alcohol then the mixture was boiled on water bath for 2 min then titrated in the presence of phenolphthalein as indicator with KOH (0.1N). Free fatty acids were calculated as a percentage of oleic acid based on the following equation (3).

$$\text{Acid value} = \frac{V \times N \times 56.11}{W} \quad (3)$$

Where: V is volume of standard potassium hydroxide (ml), N is normality of standard potassium hydroxide and Wis weight of oil (gm).

Density:

According to ASTM [33], the density of oil was determined using a 25 ml specific gravity bottle. The specific gravity bottle was weighed empty and then filled with the oil sample up to the mark on the bottle. The bottle with oil sample was weighed again. The weight of the empty bottle was subtracted from the total weight of the bottle and oil sample. The weight of the empty bottle was divided by the total weight of the bottle and oil to obtain the weight of the oil sample. The weight of the oil sample was then divided by the weight of an equal volume of water to get the specific gravity of the oil sample as following equations (4).

$$\text{Density} = \frac{\text{Mass of the substance}}{\text{Mass of an equal volume of water}} \quad (4)$$

Fatty acid composition:

Fatty acid composition was determined using a gas chromatograph (GC) equipped with a flame ionization detector (FID) at the Central Laboratories Network, National Research Centre, Cairo, Egypt. Samples underwent an alkali-catalyzed reaction with methanol in the presence of 2M potassium hydroxide to convert fatty acids into their corresponding fatty acid methyl esters (FAMEs) for injection into the GC. The analysis utilized a GC model 7890B (Agilent Technologies) equipped with a Zebron ZB-FAME column (60 m x 0.25 mm internal diameter, 0.25 µm film thickness). Hydrogen served as the carrier gas at a flow rate of 1.8 mL/min. A split-injection mode (1:50) was employed with an injection volume of 1 µL. The temperature program involved holding the initial temperature at 100 °C for 3 minutes, followed by a ramp of 2.5 °C/min to 240 °C, which was then held for 10 minutes. Both the injector and detector temperatures were maintained at 250 °C and 285 °C, respectively.

- Scanning Electron Microscopy (SEM)
Leather samples (1 cm²) were obtained from designated sampling areas as per ASTM [33]. These samples were then sputter-coated with gold ions using a JCF-1100E- JEOL system. Subsequently, the samples were evaluated using a JEOL JSM-IT Series electron microscope. To provide a comprehensive analysis, two micrographs were captured for each sample at cross-section and surface morphology.

- Tanned leather properties:
All leather samples underwent a comprehensive evaluation following completion. This involved a series of physical and chemical properties conducted in accordance with ASTM standards [33]. To ensure consistent testing conditions, the specimens were pre-conditioned for 48 hours in a controlled environment maintained at 20 ± 2 °C and 65 ± 4% relative humidity. Physical properties including density, thickness, tensile strength, elongation at break, and split tear strength were evaluated. The reported values represent the average of five measurements taken along the backbone and others across the backbone. Chemical characteristics assessed were moisture content, total ash content, fat content, and pH.
- Statistical analysis:
Data were analyzed with SAS program [34] using general linear model (GLM) procedure for analysis of variance. Means were significantly separated using Duncan's multiple range tests. The fixed effect model used was:

$$Y_{ijk} = \mu + C_i + M_j + CM_{ij} + e_{ijk}$$

Where Y_{ijk} is the observation taken (k), μ is an overall mean, C_i is a fixed effect of the (i) fatliquor concentration (5, 10, 15 or 20%), M_j a fixed effect of the (j) fatliquor material (SCGs or fish-oil), CM_{ij} is an interaction effect between fatliquor concentration and material, and e_{ijk} is a random error assumed to be normally distributed with mean=0 and variance=σ^2e.

3. Results and Discussion

- Characteristics of SCGs
Table 2 shows the moisture content of SCGs to be 66%, which aligns with the findings of Jin *et al.* [27] who reported 62%. Higher moisture content can negatively impact both oil quality and extraction yield. Therefore, thorough drying is crucial before utilizing SCGs for oil extraction.
The fat content of the SCGs, determined by Soxhlet extraction, was 14.8%. This value is consistent with the range reported by Jin *et al.* [27] of 11.8% to 14.3%, obtained using three different extraction methods.

Table 2. Characteristics of spent coffee grounds

Parameter	Value	Unit
Moisture	66	%
Ash	3.21	%
Fat	14.8	%
Density	0.72	gm/cm^3

- Characteristics of extracted SCGs oil
Analysis of the extracted SCGs oil revealed several key properties (Table 3). The SCGs oil is dark brown in color, similar to the color of SCGs. The extraction yield, at 12.12% on a dry weight basis, exceeded the value reported by Karmee [35] (10%) but aligned well with the range of 10-12% found in coffee beans by Oliveira *et al.* [26] and the 10-15% range documented by Uddin *et al.* [36] for SCGs. This reinforces the established range for oil concentration in common coffee species.

Table 3. Spent coffee grounds oil characteristics

Parameter	Value	Unit
Extraction yield*	12.12	%
Iodine value	86.19	gm I_2/100 gm oil
Saponification value	203.99	mg KOH/ gm oil
Acid value	4.53	mg KOH/ gm oil
Density	0.91	gm/cm^3
Color	Dark brown	

** Calculated based on dry weight of spent coffee grounds.*

The iodine value of the oil (86.19 gm I_2 /100 gm oil) fell within the typical range for non-drying oils (80-129 gm I_2 /100 gm oil) as reported by Wintana [37]. This value aligns with common fats like palm oil, neatsfoot oil, and beef tallow (32-81 gm I_2 /100 gm oil) according to BASF [1]. Similar findings were reported by Bijla *et al.* [38] with an iodine value of 92.22 gm I_2 /100 gm oil for their extracted oil, suggesting a high content of saturated fatty acids and non-drying properties.
The saponification value of the oil (203.99 mg KOH/gm oil) was comparable to neatsfoot oil, palm oil, and beef tallow fats (190-210 mg KOH/gm oil) as reported by BASF [1], though higher than that reported by Bijla *et al.* [38] (187.5 mg KOH/gm oil). A higher saponification value indicates shorter fatty acid chains, potentially leading to better penetration into leather and improved softness in finished products [37].

The acid value of the oil (4.53 mg KOH/gm oil) aligned well with Lauberts *et al.* [19] who reported values ranging from 4.74 to 5.58 mg KOH/gm oil for hexane extraction (lower free fatty acid content) compared to Soxhlet extraction (6.63 to 6.93 mg KOH/gm oil). It was also lower than the 15.42 mg KOH/gm oil reported by Uddin *et al.* [36]. This value falls within the range typically observed for neatsfoot and palm oil (1 to 6 mg KOH/gm oil) used in fatliquoring [1], indicating minimal breakdown of triglycerides and good oil quality. For fatliquor preparation, an acid value below 8.6 mg KOH/gm oil is recommended [37]. Finally, the SCGs oil's density (0.91 gm/cm^3) was consistent with the range reported by Caetano *et al.* [39] (0.91 to 0.94 gm/cm^3) for extracted SCGs oil and by Uddin *et al.* [36] (0.93 gm/cm^3).

- Fatty acid composition of extracted SCGs oil:
  Table 4 and Figure 1 depict the fatty acid profile of the extracted oil from spent SCGs. The composition can be categorized into two main groups: saturated fatty acids (SFAs) and unsaturated fatty acids (UFAs). As shown in the table, SFAs accounted for 47% of the total fatty acids, while UFAs comprised 52.77%, resulting in a ratio of saturated to unsaturated fatty acids of 1:1.12, respectively.

Table 4. Fatty acid composition of extracted spent coffee grounds oil.

	Fatty acids		Percentage
Saturated	C12:0	Lauric acid	0.45
	C14:0	Myristic acid	0.14
	C16:0	Palmitic acid	35.13
	C18:0	Stearic acid	7.54
	C20:0	Arachidic acid	3.19
	C22:0	Behenic acid	0.40
	C24:0	Lignoceric acid	0.15
	Total		47.00
Unsaturated	C18:1	Oleic acid	10.63
	C18:2	Linoleic acid	41.04
	C18:3	Linolenic acid	0.73
	C20:1	Gadoleic acid	0.37
	Total		52.77
	Unknown		0.23
	Total		100.00

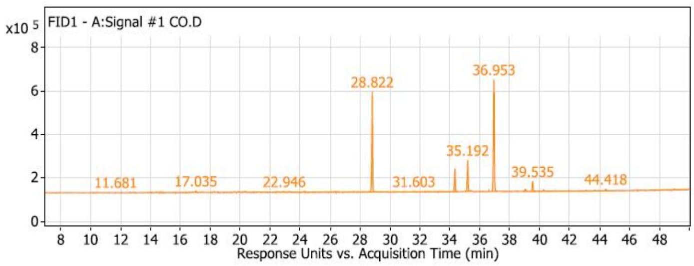

Fig. 1. Chromatogram of Fatty acids analysis for extracted oil

Linoleic acid (41.04%) was the most abundant fatty acid and the major UFA, constituting approximately 77.77% of the total UFAs. Palmitic acid (35.13%) was the second most prevalent fatty acid, followed by lower levels of stearic and oleic acids. Arachidic acid had the lowest content.

This identification of saturated and unsaturated fatty acids using gas chromatography (GC) aligns with the findings of Cante *et al.* [40]. They reported palmitic acid (C16:0) as a major component, ranging from 32.86% to 36.98%, and linoleic acid (C18:2) as another major component, ranging from 40.11% to 45.35%. Stearic acid (C18:0) and oleic acid (C18:1) were identified as minor components, ranging from 7.5% to 7.8% and 8.3% to 8.7%, respectively.

Hajib *et al.* [41] highlight that fatty acids are the principal and crucial components of oils, with a significant influence on their nutritional value, stability, and cosmetic properties. Our GC analysis revealed that the majority of fatty acids in the extracted oil are unsaturated. This characteristic makes them suitable for leather fatliquoring applications. The presence of double bonds in UFAs facilitates the sulfation reaction during fatliquoring by breaking the bond and enabling the reaction to proceed [37].

- Scanning Electron Microscopy (SEM):
  Figures 2 and 3 present scanning electron micrographs (SEM) of cross-sections (40x magnification) and surfaces (100x magnification) for all leather groups. The micrographs reveal a trend: higher fatliquor concentrations (15% and 20%) resulted in a denser, less porous internal structure and a softer surface texture, regardless of the fatliquor source (fish-oil or SCGs oil). This indicates that fatliquoring compromise the compactness and smoothness of the leather, which are desirable qualities for many applications [1,2].

  Interestingly, the micrographs also reveal differences between fish-oil and SCGs oil (SCGs) leathers at the same concentration. This suggests the type of oil used can influence the leather's microstructure and surface characteristics. Notably, SCGs oil-treated leathers appear to have a slightly more homogenous and uniform structure, potentially leading to improved physical properties and a more consistent appearance.

In light of these findings, achieving optimal leather quality requires a careful balance between fatliquor concentration and source selection. This balance should consider the desired compactness, porosity, and surface texture for the final product.

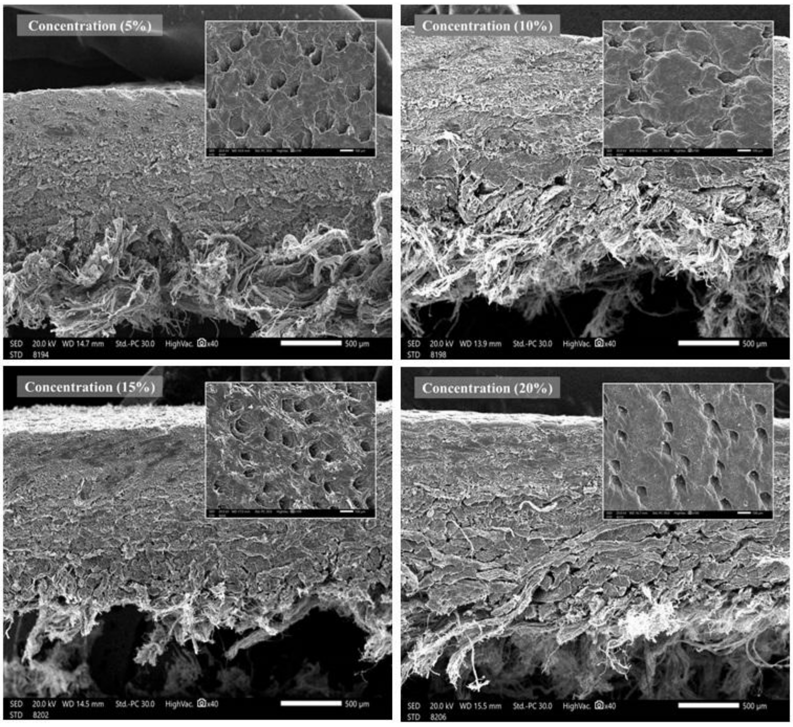

Fig. 2. Scanning electron micrographs of tanned leathers treated with different concentrations of fish oil fatliquor; cross section depicted at 40x and surface depicted at 100x.

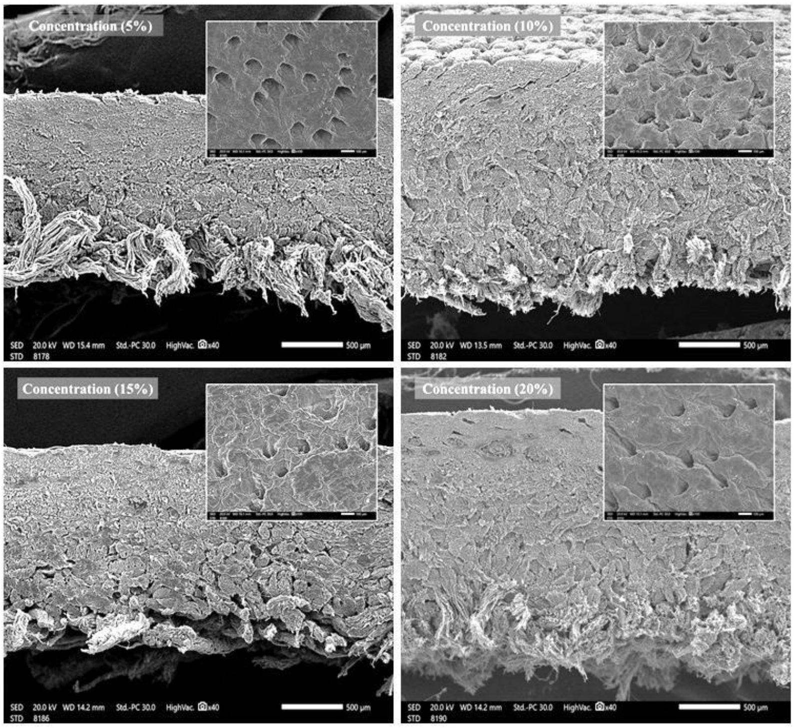

Fig. 3. Scanning electron micrographs of tanned leathers treated with different concentrations of coffee oil fatliquor; cross section depicted at 40x and surface depicted at 100x.

- Physical properties of tanned leathers:

Table 5 presents a detailed analysis of the physical properties of tanned leathers treated with spent coffee grounds (SCGs) or fish-oil fatliquors at various concentrations (5%, 10%, 15%, 20%).

Leathers fatliquored with SCGs oil exhibited significantly greater thickness (1.28 mm) than those with fish-oil (1.08 mm), indicating better filling. Conversely, fish-oil resulted in a higher density (0.93 g/cm³ vs. 0.77 g/cm³), suggesting more effective penetration within the leather matrix. In mechanical properties, SCGs fatliquor provided superior tensile strength (186.23 kg/cm²) and elongation (88.36%), while tear strength showed no significant difference. These findings demonstrate that the fatliquor source greatly influences leather properties; SCGs enhance filling, strength, and flexibility, whereas fish-oil yields denser leather.

Increasing fatliquor concentration from 5% to 15% significantly improved leather thickness (1.23 mm to 1.31 mm), but a further increase to 20% reduced thickness to 1.13 mm, indicating an optimal concentration for maximizing thickness and fullness. Tensile strength peaked at 10% fatliquor (301.87 kg/cm²), with lower values at 5%, 15%, and 20%. Tear strength also peaked at 10% (53.65 kg/cm). Elongation steadily increased with concentration, from 73.27% at 5% to 90.40% at 15%, highlighting greater flexibility at higher levels. Therefore, around 10% fatliquor concentration offers the best balance of properties, maximizing thickness, strength, and tear resistance.

Regarding interaction effects, Table 5 and Figures 4 and 5 indicate significant interactions between fatliquor source and concentration across all properties. For instance, the thickness difference between SCGs and fish-oil leathers was more pronounced at 15% (1.38 mm vs. 1.23 mm) than at 5% (1.33 mm vs. 1.13 mm). Likewise, tensile strength differences were magnified at 10% fatliquor (349.1 kg/cm² for SCGs vs. 254.7 kg/cm² for fish-oil).

These interactions emphasize the need to consider both fatliquor source and concentration for optimizing leather quality. Overall, SCGs fatliquor enhances filling and mechanical properties, while fish-oil contributes to density. An intermediate concentration of about 10% is optimal for achieving superior leather quality.

Table 5. Physical properties of tanned leathers as affected by oil material, concentrations and their interaction effect.

Item	Thickness	Density	Tensile	Tear	Elongation
Unit	mm	gm/cm^3	kg/cm^2	kg/cm	%
Effect of fatliquor source (O)	**	**	ns	ns	**
Fish-oil	1.08^b	0.93^a	162.63	46.17	66.23^b
Coffee oil	1.28^a	0.77^b	186.23	40.38	88.36^a
Effect of concentration (C)	*	ns	**	*	Ns
5%	1.23^{ab}	0.80	134.34^b	41.21^{ab}	73.27
10%	1.06^c	0.88	301.87^a	53.65^a	68.40
15%	1.31^a	0.80	107.99^b	35.48^c	90.40
20%	1.13^{ab}	0.92	153.52^b	42.76^{ab}	77.13
Interaction Effect (A × C)	**	**	**	*	**
Over all of means	1.18	0.85	174.43	43.27	77.30
Standard error of means	0.04	0.02	17.70	2.90	4.19

Means in the same column with different superscripts letter are significantly different (P<0.05).
*ns means not significant, * means significant at P<0.05, ** means significant at P<0.01*

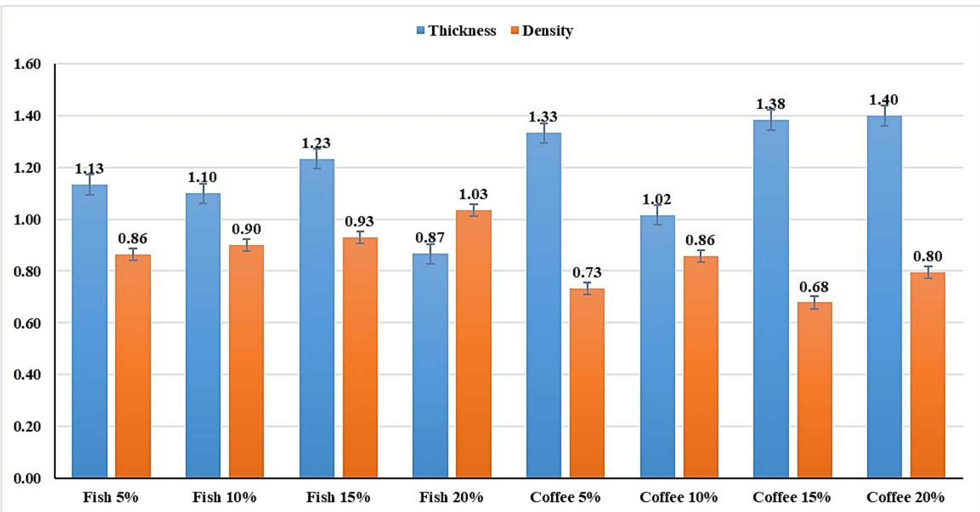

Fig. 4. Interaction effect of fatliquor material and concentration on thickness and density properties of tanned leathers

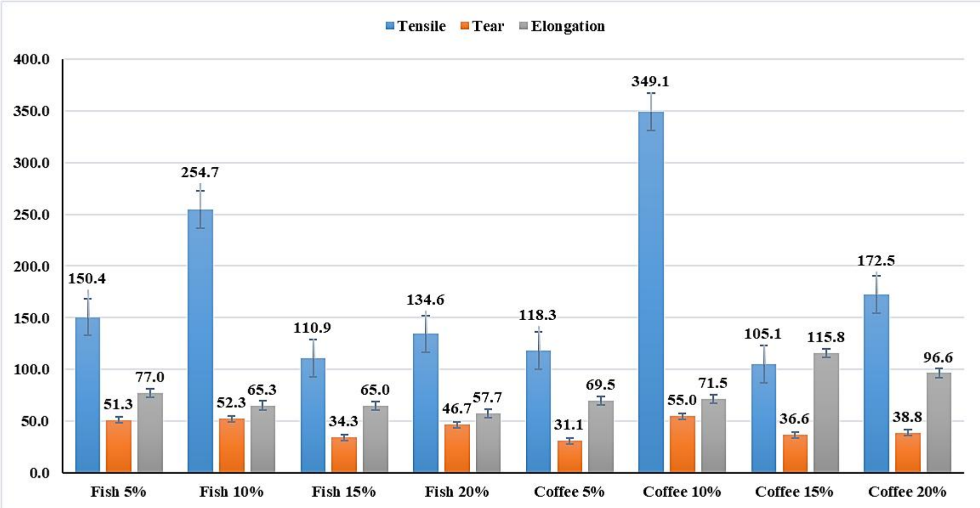

Fig. 5. Interaction effect of fatliquor material and concentration on tensile, tear strengths and elongation properties of tanned leathers.

- Chemical properties of tanned leathers:

Chemical properties of finished leathers are compared in Table 6. Leathers were treated with either SCGs or fish-oil fatliquor, applied at various concentrations (5%, 10%, 15%, and 20%). This data allows us to investigate how the fatliquor source (SCGs or fish-oil), concentration, and their combined effects influence leather quality.

The choice of fatliquor source, whether fish-oil or SGCs, did not have any statistically significant impact on the moisture, ash, fat content, or pH of the leathers. This indicates that the two fatliquor sources resulted in very similar chemical compositions of the final leathers. The lack of significant differences in pH suggests that both fish-oil and SGCs fatliquors imparted comparable acid-base characteristics to the leather. This implies that the choice of fatliquor source would not lead to major differences in the leather's chemical stability or interactions with other materials during further processing or end-use.

Increasing the fatliquor concentration from 5% to 20% did lead to a significant increase in the fat content of the leathers, rising from 2.91% to 8.88%. This is an expected result, as higher levels of fatliquoring would incorporate more of the lubricating oils into the leather matrix. However, the moisture, ash, and pH of the leathers were not significantly affected by the changes in fatliquor concentration. This suggests that the physical property improvements observed at intermediate fatliquor levels (around 10%) were achieved without causing major disruptions to the overall chemical stability and composition of the leather.

Table 6. Chemical properties of tanned leathers as affected by oil material, concentrations and their interaction effect.

Item	Moisture	Ash	Fat	pH
Unit	%	%	%	mmol/L
Effect of fatliquor source (O)	ns	ns	ns	ns
Fish-oil	12.41	4.44	5.81	4.24
Coffee oil	12.54	4.61	4.58	3.87
Effect of concentration (C)	ns	ns	**	ns
5%	12.42	4.30	2.91[c]	4.43
10%	12.70	4.46	4.16[ab]	4.21
15%	12.62	4.56	4.82[ab]	3.74
20%	12.16	4.79	8.88[a]	3.83
Interaction Effect (A × O)	ns	ns	**	ns
Over all of means	12.47	4.52	5.19	4.05
Standard error of means	0.17	0.13	0.50	0.08

Means in the same column with different superscripts letter are significantly different (P<0.05).
*ns means not significant, * means significant at P<0.05, ** means significant at P<0.01*

Table 6 and Figure 6 reveal a significant interaction effect between fatliquor source (SCGs vs. fish oil) and concentration on the final fat content of the leathers. This indicates that the impact of fatliquor concentration on leather fat content depended on the type of oil used. For instance, at a high concentration of 20%, fish oil-fatliquored leathers exhibited a greater fat content compared to those treated with SCGs fatliquor. However, at a lower concentration of 5%, the difference in fat content between the two fatliquor sources became much smaller.

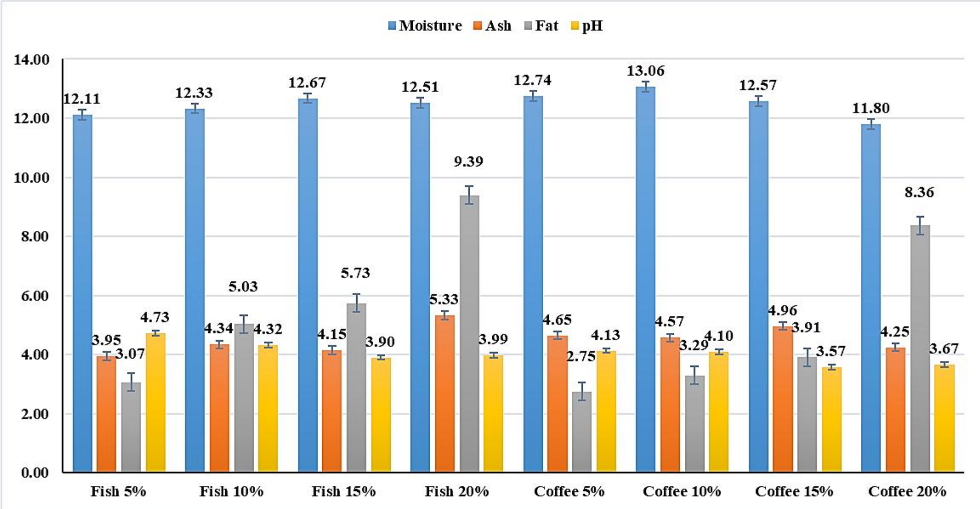

Fig. 6. Interaction effect of fatliquor material and concentration on moisture, ash, fat contents and pH properties of tanned leathers.

This interaction effect implies that the ability of the two oils to penetrate and distribute within the leather matrix may be influenced by the concentration at which they are applied. The more efficient incorporation of fish-oil at higher fatliquor levels could contribute to the differences in physical properties observed earlier, despite the lack of significant differences in overall chemical composition.

Finally, the chemical analysis indicates that the choice of fatliquor source, whether fish-oil or SCGs fatliquors, did not result in any statistically significant differences in the moisture, ash, fat, or pH properties of the leathers. The primary impact was observed in the fat content, which increased with higher fatliquor concentrations, with a significant interaction effect between fatliquor source and concentration. These findings suggest that the physical property differences observed were likely due to the inherent lubricating and filling capabilities of the two oils, rather than major changes in the overall leather chemistry.

4. Conclusion

The results of this study demonstrate the viability of using SCGs fatliquor as an eco-friendly and sustainable alternative to traditional fish-oil in the leather fatliquoring process. The extracted SCGs oil, with its favorable fatty acid profile, was successfully converted into an aqueous grease and applied to sheep wet-blues at various concentrations.

The analysis of the resulting leathers revealed that SCGs fatliquor can provide comparable, and in some cases, superior quality compared to the conventional fish-oil-fatliquored leathers. Notably, the SCGs fatliquored leathers exhibited a more homogeneous and uniform microstructure, which may contribute to improved physical properties and a more consistent appearance. Additionally, the SCGs fatliquor demonstrated good filling and mechanical properties, with an optimal concentration around 10% for maximizing overall leather quality.

The use of SCGs fatliquor offers significant environmental and economic benefits. By utilizing a waste material like SCGs, this approach promotes sustainability and reduces the industry's reliance on finite marine resources. Furthermore, the implementation of SCGs fatliquor can contribute to the circular economy by valorizing a by-product and enhancing the overall environmental footprint of the leather tanning process.

5. Author Contributions

Conceptualization – El Shaer MA; Methodology – El Shaer MA, Kassem ST, Alfawal GS, Abd-Elhamed W, Abd-Elraheem MA; Formal analysis – Nasr AI; Investigation – El Shaer MA, Alfawal GS, Abd-Elhamed W; Resources – El Shaer MA, Abd-Elraheem MA; Writing-original draft preparation – Alfawal GS; Writing-review and editing– Nasr AI; Visualization –Nasr AI; Supervision – Nasr AI, El Shaer MA. All authors have read and agreed to the published version of the manuscript.

6. Conflicts of Interest

The authors declare no conflict of interest.

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