Jurnal Veteriner pISSN: 1411-8327; eISSN: 2477-5665
Terakreditasi Nasional Peringkat 2, Dirjen Riset dan Pengembangan,
Kemendiktisaintek RI SK No 10/C/C3/DT.05.00/2025, 21 Mar.2025

Juni 2026 Vol. 27 No. 2: 273-288
DOI: 10.19087/jveteriner.2026.27.2.273
online pada http://ejournal4.unud.ac.id/index.php/juvet

Physical and Microstructural Characteristics of Chicken Feet Skin Tanned with Local Vegetable Agents as Premium Leather Alternatives

(KARAKTERISTIK FISIK DAN MIKROSTRUKTURAL KULIT KAKI AYAM YANG DISAMAK DENGAN BAHAN NABATI LOKAL SEBAGAI ALTERNATIF KULIT PREMIUM)

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ABSTRACT

Abundant chicken feet skin waste remains underutilized despite its potential as high value exotic leather due to its unique natural scale patterns. This study was aimed to evaluates the utilization of broiler chicken feet skin through eco-friendly tanning by using local vegetable extracts: Sappan wood (*Caesalpinia sappan*), Acacia wood (*Acacia* sp.), and tea leaves (*Camellia sinensis*), with commercial textile dye as a control. A completely randomized design with four treatments and three replications ($\eta=3$) was employed. Raw material analysis revealed a proximate composition favorable for collagen-based tanning, dominated by a crude protein fraction of 25.67 ± 0.58. Results indicated that tanning agents significantly affected ($p< 0.05$) physical and mechanical properties. The highest thickness was observed in the Acacia treatment (0.54 ± 0.01 mm). While the control exhibited the highest tensile strength, Acacia yielded the highest strength among vegetable groups (1860.17 ± 10.00 N/cm²) but recorded the lowest elongation (19.68 ± 0.25%), indicating increased tissue stiffness. Tea leaf extracts produced the highest tear resistance among vegetable treatments (300.81 ± 0.20 N/cm). Scanning Electrone Microscope (SEM) confirmed consistent differences in porosity and micro cracking across treatments. These findings confirm that local vegetable tanning is a viable waste to resource strategy for producing sustainable, premium oriented alternative leather

Keywords: Chicken feet Skin; Local Tannins; Mechanical Properties of Leather; SEM Microstructure; Vegetable Tanning

ABSTRAK

Limbah kulit ceker ayam yang melimpah masih belum teroptimalkan sebagai material bernilai tinggi, padahal memiliki pola sisik alami yang berpotensi menggantikan kulit eksotis dan dapat diproses dengan penyamakan yang lebih ramah lingkungan. Studi ini bertujuan mengevaluasi pemanfaatan kulit ceker ayam pedaging atau *broiler* sebagai material kulit alternatif melalui penyamakan nabati lokal menggunakan ekstrak kayu secang (*Caesalpinia sappan*), kayu akasia (*Acacia* sp.), dan daun teh (*Camellia sinensis*), dengan kontrol berupa pewarna tekstil komersial. Penelitian ini menggunakan rancangan acak lengkap dengan empat perlakuan dan tiga ulangan (n = 3) untuk pengujian fisik mekanik; mikrostruktur dianalisis menggunakan *scanning electrone microscop*e (SEM). Bahan baku menunjukkan komposisi proksimat yang mendukung potensi penyamakan berbasis kolagen, yaitu kadar air 60,00 ± 2,00%, protein 25,67 ± 0,58%, lemak 7,00 ± 1,00%, dan abu 7,00 ± 1,00%. Perlakuan yang diberikan berpengaruh nyata ($p < 0{,}05$) terhadap ketebalan dan sifat mekanik kulit ceker ayam. Ketebalan tertinggi diperoleh pada perlakuan akasia (0,54 ± 0,01 mm) dan terendah pada kontrol (0,44 ± 0,01 mm). Kekuatan tarik tertinggi tercapai pada kontrol (3460,53 ± 10,00 N/cm²), sedangkan pada kelompok nabati akasia memberikan kekuatan tarik tertinggi (1860,17 ± 10,00 N/cm²) namun kemuluran terendah (19,68 ± 0,25%), mengindikasikan peningkatan kekakuan jaringan. Ketahanan sobek tertinggi pada perlakuan nabati diperoleh daun teh (300,81 ± 0,20 N/cm), lebih tinggi dibanding secang (196,24 ± 0,20 N/cm) dan akasia (151,39 ± 0,20 N/cm). Secara makroskopis, agen nabati menghasilkan variasi intensitas warna dan homogenitas permukaan yang relevan bagi keterbacaan grain/pola sisik, sedangkan SEM menunjukkan perbedaan porositas dan retakan mikro yang konsisten sebagai faktor penentu konsentrasi tegangan dan variasi respons mekanik. Temuan ini menegaskan prospek penyamakan nabati lokal sebagai strategi *wasteto resource* untuk mengonversi limbah kulit ceker ayam menjadi material kulit alternatif yang lebih berkelanjutan dan berorientasi aplikasi premium.

Kata-kata kunci: kulit ceker ayam; penyamakan nabati; tanin lokal; sifat mekanik kulit; mikrostruktur SEM

INTRODUCTION

The global leather industry stands at a crossroads between market demands and sustainability pressures. On one hand, the fashion and luxury goods segments require materials with high aesthetic value, characterized by distinctive grain patterns, exotic appearances, and visual consistency. On the other hand, the leather supply chain faces strengthening chemical and product safety regulations, particularly concerning residues and the formation of hexavalent chromium (Cr(VI)) in leather articles that come into contact with human skin (Chen *et al*., 2023; Malabadi *et al*., 2025). In the European Union, restrictions on Cr(VI) in leather goods have been enforced through the Registration, Evaluation, Authorisation and Restriction of Chemicals. (REACH) framework, establishing a threshold of ≥ 3 mg/kg (based on the dry weight of the leather) as the basis for non compliance for skin contact products. The presence of Cr(VI) is regarded as a significant toxicological and consumer safety issue, thereby reinforcing the urgency of transitioning toward safer and more sustainable tanning processes (Celik, 2024).

Beyond chemical concerns, exotic leather materials derived from reptiles have also drawn attention regarding conservation and animal trade ethics. Consequently, research into alternative leather materials is expanding toward chrome free tanning and the utilization of biomass or waste as value added raw material sources, aligning with the principles of a circular economy (Battal et al., 2025). Current literature confirms an increasing focus on greener tanning technologies, including the use of organic or vegetable tanning agents and processing systems that minimize environmental pollution loads. However, the primary challenge for alternative approaches is not merely "reducing environmental impact," but ensuring that functional quality (physical durability) and aesthetic quality continue to meet the expectations of the premium market (Jiang *et al*., 2023).

In this context, the by products of the poultry industry specifically the skin of broiler chicken feet offer unique biomaterial opportunities. Indonesia possesses a vast production base for broilers; official publications from the Ministry of Agriculture (Pusdatin) reported that the national broiler population reached 3.19 billion birds in 2023 and is projected to continue increasing during the 2025–2029 period to a range of 3.40–3.68 billion birds. This production scale has direct implications for the abundant and recurring (daily) availability of slaughterhouse by product biomass. Simultaneously, chicken feet skin possesses distinct surface characteristics in the form of unique scale patterns. Studies in leather technology indicate that chicken feet skin can be processed into leather sheets with attractive grain, suitable for fashion products and accessories, thereby opening prospects as an "exotic" alternative material based on poultry waste (Ricke *et al.*, 2025).

Nevertheless, the valorization of chicken feet skin for premium value applications cannot be treated as a direct extension of conventional tanning practices. Targeting premium materials demands two simultaneous achievements: (i) the stabilization of the collagen structure to ensure adequate physical durability, and (ii) the retention of scale patterns as the primary visual identity (Santana *et al.,* 2020). In many alternative leather studies, the evaluation of tanning success often remains limited to basic process feasibility or specific macroscopic parameters; meanwhile, the relationship between tanning agents, microstructural changes, grain/surface pattern retention, and physical performance has not been robustly mapped, especially for chicken feet skin, which differs morphologically from mammalian skin (Yorgancioglu *et al*., 2022).

On the other hand, vegetable tanning approaches are regaining attention due to their potential as a chrome free pathway that aligns more closely with the sustainability agenda. Chemically, tannins as polyphenols are capable of interacting with collagen and forming bonding networks that enhance leather stability (Xiao *et al.*, 2023). Indonesia possesses diverse and relatively accessible sources of local tannins, including Sappan wood (Caesalpinia sappan), which has been reported as a potential tannin source for chromium substitution in the tanning process, and Acacia (*Acacia* sp.), widely known as a source of vegetable tannins for tanning applications. Additionally, tea leaves (*Camellia sinensis*) are rich in polyphenols (catechins), which are classified as condensed tannins and have the potential to be used as vegetable based tanning agents. However, comprehensive comparisons among these local vegetable tanning agents in the context of chicken feet skin with a simultaneous emphasis on the aesthetics of scale patterns and testing standard based physical parameters remain rarely reported (Vegetable Tanning, 2019).

Based on the aforementioned descripttion, the prominent research gap is the lack of integrated experimental evidence regarding how variations in local vegetable tanning agents influence scale pattern retention, surface aesthetics, key physical properties of the tanned leather, and the microstructural changes that explain the quality formation mechanism in chicken feet skin. Without this comparative understanding, chicken feet skin tends to remain positioned as a low value by product rather than a candidate biomaterial that can be standardized for the premium segment.

Consequently, this research focuses on developing a comparative evaluation framework for eco-friendly tanning using three local vegetable tanning agents to optimize the transformation of chicken feet skin into a material with an exotic appearance. Diverging from approaches that only assess general process success, this study positions scale pattern retention as a key aesthetic parameter and correlates it with physical parameters and microstructural indicators to explain the tanned leather quality more scientifically (Hidalgo, 2016; Iade *et al.,* 2013). This research was aimed to analyze the influence of each local vegetable tanning agent on the physical and microstructural characteristics of chicken feet skin, as well as to identify the most effective tanning agent in producing a material with an optimal balance between scale pattern aesthetics and functional performance. The contribution of this research is expected to provide an understanding of the tanning agent microstructure performance relationship in chicken feet skin and serve as a foundation for developing local resource-based waste to resource processes to strengthen the circular economy and reduce dependence on chromium based tanning systems (Machado *et al*., 2013).

RESEARCH METHODS

Experimental Design

This study employed a Completely Randomized Design (CRD) featuring four tanning treatments: a commercial control group (P1) and three vegetable tanning treatments utilizing extracts from Sappan wood (Caesalpinia sappan), Acacia wood (Acacia sp.), and tea leaves (*Camellia sinensis*) (P2–P4) (Nurlisa *et al.,* 2015). Each treatment was conducted in triplicate (three replications), resulting in a total of 12 experimental units. One replication was defined as eight (8) pieces of broiler chicken feet skin processed under identical treatment conditions. A total of n = 100 broiler chicken feet were utilized as raw material in this study. The skins obtained after the flaying process were randomly allocated into treatments P1–P4 before the tanning process and subsequent testing .

Raw Material and Skin Preparation

Fresh broiler chicken feet (shank portion) were obtained from birds with an average live slaughter weight of 2.5 kg/head. Samples were collected from a commercial poultry slaughterhouse in Makassar City, Indonesia, which has a production capacity of approximately 100 birds per day, where chicken feet are generated as slaughterhouse by products. Following collection, the chicken feet were placed in sterile plastic containers and transported to the laboratory under cold conditions (±4°C). The entire initial processing was conducted within less than hours post slaughter to minimize the degradation of collagen tissues (Hashim *et al*., 2015).

Prior to skin separation, the chicken feet were washed under running water to remove residual blood and impurities. The initial weight of the samples was measured using a digital analytical balance (Ohaus, USA; precision 0.001 g). Skin separation (flaying) was performed manually using sterile scalpels by incising the base and stripping the skin layer from the bone and muscle tissues. Residual adipose tissue (fleshing) and connective tissues were carefully removed to obtain uniform skin layers (Zou and Maibach, 2018). The separated skins were rinsed twice with distilled water, then grouped into replication units (8 pieces of skin per replication) for subsequent random allocation to each treatment (Figure 1).

To inhibit microbial growth prior to the tanning process, the skins were soaked in a 10% (w/v) sodium chloride (NaCl) solution for 30 minutes. After soaking, the skins were drained for 10 minutes (Cadirci *et al*., 2010), and the wet weight was rerecorded. The initial skin thickness was measured using a digital thickness gauge (Mitutoyo, Japan; resolution 0.01 mm) at three different points, with the average value serving as the representative initial thickness of the sample.

Pre tanning Treatment

To enhance the penetration of tanning

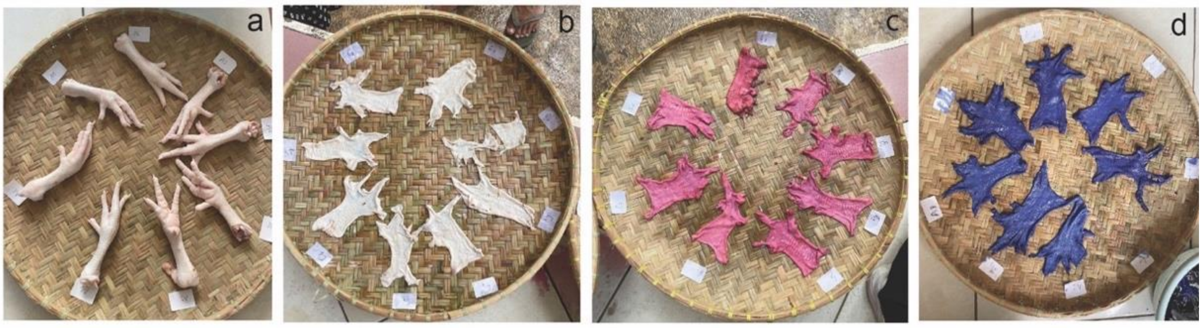

Figure 1. Macroscopic appearance of broiler chicken feet skin across different treatments: (a) Raw skin prior to processing; (b) Skin after tea leaf (Camellia sinensis) tannin treatment; (c) Skin after Sappan wood (Caesalpinia sappan) tannin treatment; (d) Skin after commercial textile dye treatment (control).

agents into the collagen matrix, the skins underwent pre tanning stages consisting of rehydration and degreasing (Sizeland et al., 2016). The skin samples were soaked in distilled water at a solution volume to skin weight ratio of 10:1 (v/w) for 30 minutes at room temperature to remove residual salts. Subsequently, the skins were immersed in a 1% non ionic detergent solution for 20 minutes with gentle agitation using a magnetic stirrer (IKA, Germany). After cleaning, the skins were rinsed with distilled water until free from detergent residues and then drained.

Preparation of Tanning Solutions

This study employed four tanning treatments to evaluate the balance between mechanical structural integrity and skin aesthetics, consisting of one control treatment (P1) and three vegetable tanning agents (P2, P3, and P4). Control treatment (P1): utilized a commercial textile dye. The solution was prepared by mixing 125 mL of dye into 500 mL of distilled water, and subsequently homogenized using a magnetic stirrer for 10 minutes.

Vegetable extracts (P2, P3, and P4): utilized Sappan wood (*Caesalpinia sappan*) extract for P2, Acacia (*Acacia* sp.) for P3, and tea leaves (*Camellia sinensis*) for P4 (Vij et al., 2023). Extraction was performed using the hot water extraction method to retrieve phenolic compounds and tannins (Covington, 2009; Thanikaivelan *et al*., 2005). A total of 10 g of dried plant material was boiled in 500 mL of distilled water at 95°C for 60 minutes on a hot plate stirrer (IKA, Germany). Following extraction, the solution was cooled to room temperature (±27°C) and filtered using Whatman No. 1 filter paper to separate solid residues from the filtrate.

Leather Tanning Process

The prepared skins were immersed in their respective tanning solutions (P1, P2, P3, and P4), maintaining a solution volume to wet skin weight ratio of 10:1 (v/w). The tanning process commenced with active stirring using a magnetic stirrer for 30 minutes to facilitate the penetration of tanning agents into the skin tissues, followed by static soaking for 2 hours at room temperature (±27°C) (Rosiati & Udkhiyati, 2022). After the tanning process was completed, the skins were rinsed again with distilled water to remove residual unbound tannins.

Drying and Material Stabilization

The tanned skins were dried using a controlled drying method. Samples were stretched on toggling frames and placed in a drying oven (Memmert, Germany) at 40°C for 24 hours until a constant weight was achieved. Once dried, the samples were conditioned at 25 ± 2°C with a relative humidity of 50 ± 5% for 24 hours to stabilize the moisture content before testing (Zhang *et al*., 2024).

Physical and Mechanical Property Testing

Physical and mechanical testing was conducted at the Center for Standardization and Industrial Services for Leather, Rubber, and Plastics (BBSPJIKKP), Yogyakarta, Indonesia. The evaluated parameters included: skin thickness according to ISO 2589; tensile strength and elongation at break using a Universal Testing Machine (Instron 3365, USA) according to ISO 3376; and tear strength according to ISO 3377-2. Specimens were tested at a constant extension rate until rupture or tearing occurred (Mutlu *et al*., 2016). All tests were performed in triplicate for each treatment.

Chemical Composition Analysis

Proximate analysis was performed at the Laboratory of Fisheries and Marine Science, Hasanuddin University, Makassar. The analyzed parameters included moisture content (%), crude protein (%), fat content (%), and ash content (%). Moisture content was determined using the oven drying method at 105°C until a constant weight was achieved (AOAC 950.46). Crude protein content was analyzed using the Kjeldahl method (AOAC 2001.11) with a nitrogen conversion factor of 6.25. Fat content was extracted using the Soxhlet method with petroleum ether as the solvent (AOAC 991.36). Ash content was determined by incineration at 550°C for 4 hours (AOAC 920.153) (Ali *et al.*, 2023). All analyses were conducted in triplicate.

Microstructural Analysis

The morphological characteristics of the skin surface and cross sections were observed using a Scanning Electron Microscope (SEM; JEOL JSM-6510LV, Japan). Samples were cut into approximately 5 mm × 5 mm specimens and ensured to be in a dry condition. The samples were mounted onto aluminum stubs using double sided carbon tape and subsequently coated with a conductive layer (gold/palladium) using a sputter coater (Quorum Technologies, UK). Observations were performed at an aceleration voltage of 10–15 kV at various magnifications to evaluate collagen fiber homogeneity, porosity, and indications of defects or cracks in the skin matrix resulting from the tanning process (Buchanan *et al.*, 2019).

Data Analysis

Quantitative data are presented as mean values ± standard deviation. The effects of tanning treatments on physical and chemical parameters were analyzed using one way analysis of variance (ANOVA). Where significant differences were observed ($p < 0.05$), the analysis was followed by Tukey’s Honestly Significant Difference (HSD) test at a 5% significance level. All statistical computations were performed using SPSS version 26 (IBM Corp., USA).

RESULTS AND DISCUSSION

Proximate Analysis

The results of the proximate analysis indicated that fresh chicken feet skin contained 60.00 ± 2.00% moisture, 25.67 ± 0.58% protein, 7.00 ± 1.00% fat, and 7.00 ± 1.00% ash (Table 1). The high protein fraction confirms the dominance of structural proteins (primarily collagen) as the primary skin matrix, which determines the tanning response through the formation of cross links. The measurable fat content underscores the importance of the degreeasing stage to prevent interference with the penetration of tanning agents into the collagen tissues.

Table 1. Proximate composition of chicken feet skin

Parameter	Composition
Moisture Content (%)	60.00 ± 2.00
Protein (%)	25.67 ± 0.58
Fat (%)	7.00 ± 1.00
Ash (%)	7.00 ± 1.00

Note: Values are presented as mean ± SD (n = 3)

The proximate composition of the chicken feet skin in this study confirms that the raw material is dominated by the structural protein fraction (collagen), thus theoretically providing numerous reactive groups (–NH, –COOH, –OH) that serve as cross linking sites during the tanning process. This finding is aligned with various reports indicating that chicken feet/skin is a potential source of Type I collagen and is

Table 2. Physical properties of chicken feet skin under various tanning treatments

Treatment	Initial Weight (g)	Wet Weight (g)	Final weight (g)	Thickness (mm)
Control (textile dye),	62,875 ± 0,750^{a}	12,875 ± 0,250^{a}	0,938 ± 0,010^{a}	0,44 ± 0,01^{c}
Sappan wood	55,875 ± 0,375^{c}	10,50 ± 0,25^{b}	0,805 ± 0,010^{b}	0,49 ± 0,01^{b}
Akasia Wood	61,375 ± 0,250^{b}	11,00 ± 0,25^{b}	0,638 ± 0,010^{c}	0,54 ± 0,01^{a}
Tea Leaves	63,750 ± 0,250^{a}	12,375 ± 0,250^{a}	0,800 ± 0,010^{b}	0,50 ± 0,01^{b}

Note: Values are presented as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences based on Tukey’s HSD test ($p < 0.05$) following one way ANOVA.

frequently utilized as a substrate for collagen gelatin extraction in both food and biomaterial applications (Zourazema et al., 2025). Furthermore, the proximate composition of chicken feet raw materials reported in other studies also demonstrates that protein is the major component, although exact figures may vary depending on the reporting basis (wet weight vs. dry matter basis) and the specific sample portion analyzed (skin only vs. whole feet including bone/cartilage) (Dhakal *et al*., 2018). In other words, the "protein dominant" proximate profile in this study is consistent with the biological characteristics of chicken feet as a collagen rich tissue, supporting the rationalization of using chicken feet skin as a raw material for alternative leather.

Compared to proximate reports on whole "chicken feet," variations in fat and ash content in previous studies are generally larger due to the contribution of non skin tissues (bone, cartilage, and mineral residues) and differences in pre analytical treatments (tissue removal, drying, and conversion to dry matter basis)(Dhakal *et al.*, 2018). In the context of tanning, the presence of measurable fat in the raw material though not dominant and technically act as a barrier to the diffusion of tanning solutions and reduce fixation uniformity. This reinforces the urgency of the degreasing stage as a prerequisite to enhance the penetration and interaction of the tanning agent with the collagen matrix. Practically, the "high protein residual fat" combination in chicken feet skin in pre treatment positions (cleaning and degreasing) as a critical quality control factor to ensure the tanning process produces a more stable and uniform structure, as emphasized in the literature regarding the utilization of chicken feet skin as a collagen/biomaterial source (Razavizadeh *et al.*, 2022).

Changes in Skin Weight and Thickness During the Tanning Process

Tanning treatments resulted in signifycant differences in the initial weight, wet weight, and final weight of the chicken feet skin (Figure 1a–c). In general, the control and tea leaf treatments tended to fall within the higher value groups across several weight stages, whereas the Sappan wood treatment tended to be lower (Table 2). Differences in wet weight indicate variations in water/solution retention after soaking, which may be related to porosity and the initial interaction of the solution with the collagen matrix. The thickness of the tanned leather also differed significantly among treatments (Figure 1d). The Acacia wood treatment exhibited the highest thickness, while the control was the lowest. These changes suggest a filling effect and/or variations in the degree of fiber compaction during drying that differ between treatments.

The differences in weight across various processing stages (initial wet final) indicate that each treatment agent produces varying degrees of fluid retention and bound solid retention within the skin matrix. In principle, mass changes during the wet stage primarily reflect the capacity of the collagen tissue to absorb and retain water and

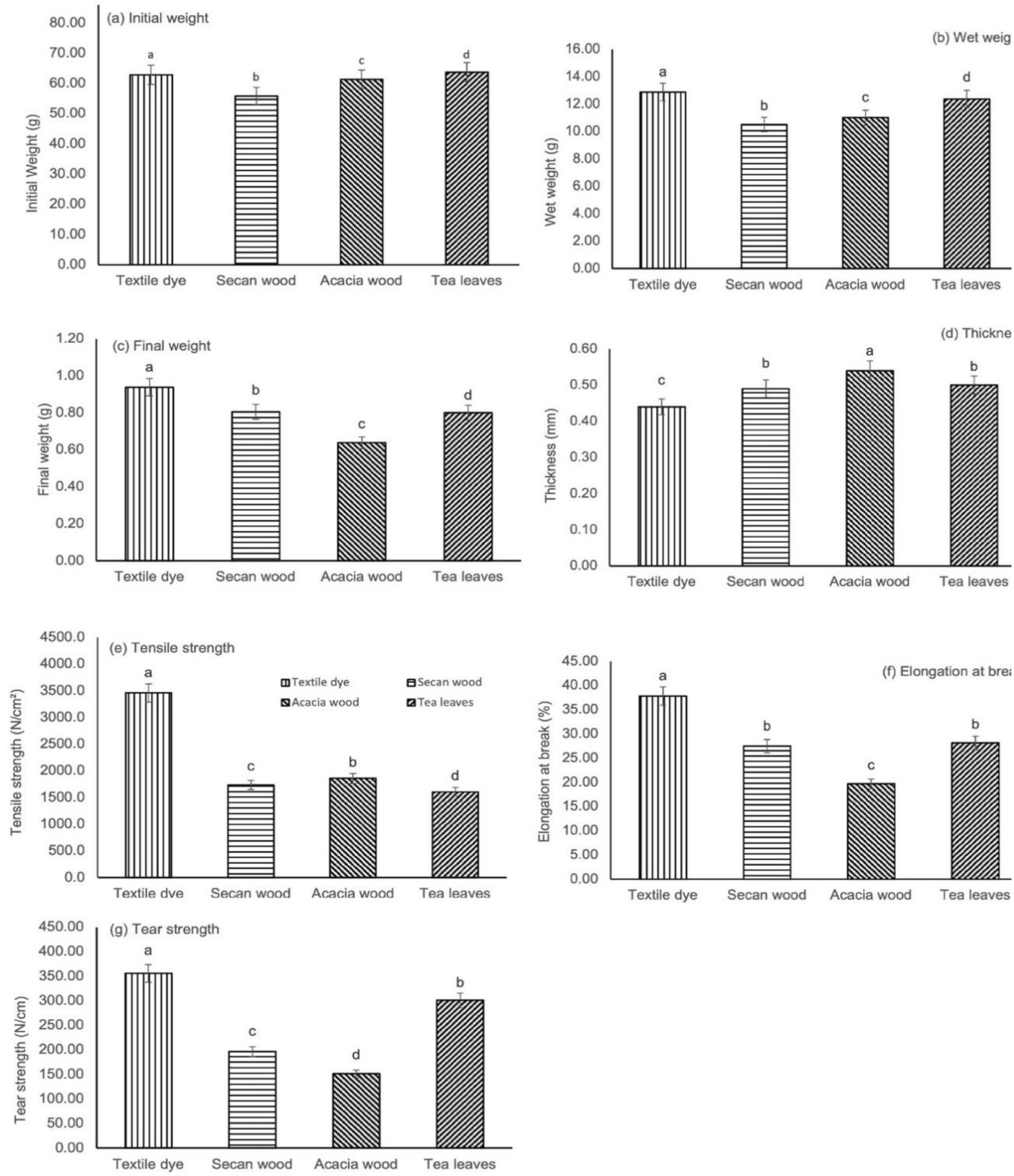

Figure 1. Effects of different tanning agents on the physical and mechanical properties of broiler chicken feet skin.

Note: (a) initial weight, (b) wet weight, (c) final weight, (d) thickness, (e) tensile strength, (f) elongation at break, and (g) tear strength across four treatments: control (textile dye), Sappan wood, Acacia wood, and tea leaves. Values are presented as mean ± SD (n = 3). Different letters within the same panel indicate significant differences (Tukey’s HSD; $p < 0.05$) following one-way ANOVA.

solutions, whereas the final mass after drying reflects the equilibrium between collagen shrinkage and the fixation of bound components. This mechanism is consistent with the fundamental concepts of tanning science, which state that the quality of "crust leather" is influenced by the penetration and fixation of agents, as well as microstructural changes during the drying process (Gamna *et al.*, 2026). Compared to studies on other poultry skins, the variations in weight and thickness among treatments are also aligned with findings that chicken leg skin possesses a distinctive grain structure and a processing

Table 3. Mechanical properties of chicken feet skin under various tanning treatments

Treatment	Tansile Strength (N/cm^2)	Elongation at Break (%)	Tear Strength (N/cm)
Control (textile dye),	3460.53 ± 10.00^{a}	37.86 ± 0.25^{a}	355.71 ± 10.00^{a}
Sappan wood	1732.96 ± 10.00^{c}	27.50 ± 0.25^{b}	196.24 ± 0.20^{c}
Akasia Wood	1860.17 ± 10.00^{b}	19.68 ± 0.25^{c}	151.39 ± 0.20^{d}
Tea Leaves	1605.11 ± 10.00^{d}	28.12 ± 0.25^{b}	300.81 ± 0.20^{b}

Note: Values are presented as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences based on Tukey's HSD test ($p < 0.05$) following one way ANOVA.

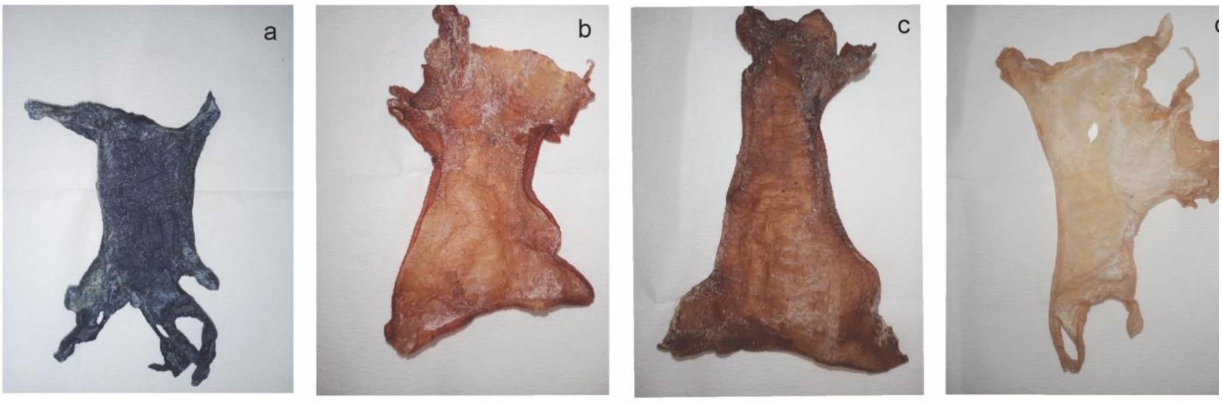

Figure 2. Appearance of chicken feet skin tanned with various tanning agents

Note: (A) Control (textile dye), (B) Sappan wood, (C) Tea leaves, and (D) Acacia wood. Photo captions were taken after the drying and conditioning processes; differences in color and surface appearance reflect the distinct characteristics of the treatment agents.

response sensitive to chemical/processing treatments; thus, variations between the wet and dry stages can emerge even when the raw materials originate from the same species (Karthikeyan *et al.*, 2017).

The differences in thickness among treatments can be understood through the "filling" effect and the degree of fiber compaction: tannin-based vegetable tanning agents tend to act as fillers (stuffing/filling) while simultaneously forming bonds with collagen, which can increase effective thickness and reduce fiber compression under certain processing conditions. Literature also indicates that the type of vegetable tanning material is a dominant factor influencing the physical characteristics of leather (including parameters related to stability and performance); thus, variations in thickness and drying response among different tannin sources represent a common pattern (Xiao et al., 2023). Consequently, the findings in Table 2 and Figure 1d confirm that different agents (Sappan wood, Acacia, and tea) not only alter the chemical fixation properties but also modulate the behavior of the collagen structure during drying, which ultimately implicates the physical characteristics of the tanned leather (Zehra *et al.*, 2023)

Mechanical Properties: Tensile and Tear Strength

Tensile strength differed significantly among treatments (Figure 1e). The control exhibited the highest value, whereas the tensile strength of the vegetable tanning treatments was at a lower level and varied among the agents. This finding indicates that the type of tanning agent produces varying degrees of collagen matrix reinforcement, thereby influencing the skin's ability to withstand tensile force until rupture. Elongation at break also differed signifycantly (Figure 1f). The control showed the highest elongation, while Acacia was the lowest. Sappan wood and tea leaves fell within the intermediate group. Lower elongation may indicate a stiffer or denser structure (more restricted fiber mobility), whereas higher elongation reflects a more elastic deformation response before failure.

Tear strength differed significantly among treatments (Figure 1g; Table 3). The control yielded the highest value. Among the vegetable treatments, tea leaves showed higher tear strength than Sappan wood and Acacia. Since tear resistance is influenced by the ability of the fiber network to resist crack propagation, this pattern indicates a matrix configuration that is relatively more resistant to tearing in the tea leaf treatment under these processing conditions.

The differences in tensile strength and elongation among the tanning agents in this study demonstrate a reinforcement flexibility trade off commonly observed in collagen based materials: as stronger interactions or cross links form, the network tends to become denser and fiber mobility decreases, leading to a shift in elongation. This pattern is consistent with vegetable tanning studies emphasizing that tannin composition (e.g., the proportion of tannins vs. non tannins and the polyphenol type) modulates network compactness, strength, and the deformation behavior of the leather. These findings align with reports on the utilization of chicken feet skin as an "exotic leather alternative," which state that chicken feet skin possesses a distinctive grain and can achieve viable mechanical properties, though its performance is sensitive to the processing pathway and the type of tanning agent used (Teshome et al., 2022). Compared to research on chicken feet skin using combinations of chrome and mimosa, which reported that mechanical parameters among treatment combinations might not differ significantly, the performance separation observed among the vegetable agents in this study indicates that in the system employed, the source of local tannins is a more decisive factor for mechanical response than the mere "presence or absence" of vegetable tanning (Beghetto *et al*., 2025).

Regarding tear strength, the tendency for one of the vegetable treatments to provide relatively better tear resistance indicates that resistance to crack propagation does not always follow tensile strength patterns linearly. Instead, it is heavily influenced by fiber network regularity, porosity, and the presence of microcracks as commonly discussed in leather characterrization literature (tensile and tear as key tests) (Ridruejo *et al.*, 2015). This helps explain why two vegetable agents might have differing tensile strengths yet show distinct tear responses: a specific agent may form a sufficiently "bound" network but remain suboptimal in resisting crack propagation, while another agent forms a fiber configuration better able to distribute tear stress. Overall, these findings reinforce messages from vegetable tanning studies that optimization is not achieved simply by selecting "tannin"; rather, it requires considering the tannin type, non tannin fractions, and processing conditions, as all three contribute simultaneously to tensile strength, elongation, and tear resistance (Fatema *et al*., 2023).

Macroscopic Appearance of Tanned Leather

The macroscopic appearance of the chicken feet skin after tanning exhibited visual differences among treatments, particularly in color intensity and surface homogeneity (Figure 2). These variations in color and surface appearance are critical in the context of developing premium value leather materials, as they are directly related to aesthetic perception (including the definition and clarity of scale/grain patterns).

The differences in macroscopic appearance among treatments in Figure 2 can be explained through the intrinsic properties of each agent, particularly the composition of polyphenols/tannins and pigments that function simultaneously as tanning agents and natural color ants. In general, vegetable tanning literature explains that leather tanned with condensed tannins tends to develop brownish to reddish hues, whereas certain groups of hydrolyzable tannins can produce paler or yellow cream tones; these differences are also influenced by processing conditions, including pH, oxidation, and the drying stage (Falcão and Araújo, 2018). In the context of this study, Sappan wood is chemically known to be rich in brazilin/brazilein pigments associated with red orange to reddish brown colors, making it plausible that the Sappan wood treatment exhibits a "warmer" and more striking color intensity. Meanwhile, variations in darkness and homogeneity in the tea leaf treatment can be attributed to polyphenols/ catechins that easily undergo oxidation to form brown colors and enhance the staining effect on the collagen matrix (Huddar and Ahmed, 2025; Omur *et al.,* 2026). Consequently, these macroscopic findings are consistent with previous studies emphasizing that the type of tannin source not only determines collagen stabilization but also produces a distinctive "color signature" and surface visual quality—critical factors for the segmentation of premium leather materials that demand color consistency, surface uniformmity, and grain/scale pattern definition as primary aesthetic values (Romer *et al*., 2011).

Microstructural Characteristics of Skin Tissue Based on SEM Examination

Scanning Electrone Microscope (SEM) analysis revealed microstructural variations among the tanned chicken feet skin treatments, observed through the presence and size of particles, pores, cracks, and fiber features (Figure 3). In the control (textile dye), particle, pore, and crack features were observable, although the "fiber" panel was recorded as unavailable (no result). In the vegetable tanning treatments (Sappan wood, tea leaves, and Acacia), all four feature categories were observable. Qualitatively, the tea leaf treatment exhibited pores that appeared more open in the "pore" panel, while cracks were observed across all treatments with varying shapes and continuity. These variations in porosity and cracking are relevant to explaining the differences in mechanical properties (specifically, tear resistance and deformation response) observed in Figure 1 and Table 2, as pores and cracks potentially serve as stress concentration sites during loading.

Microstructural variations specifically differences in porosity, deposited particles, and the emergence of cracks are consistent with the understanding that the tanning process (particularly polyphenol/tannin-based systems) operates through diffusion, adsorption, and bond formation within the collagen structural hierarchy. "Green tanning" literature emphasizes that polyphenols/tannins possess a high affinity for collagen and are capable of forming bonding networks (hydrogen, coordination, or covalent, depending on the system) that alter fibril density and organization. These changes are frequently manifested in SEM as differences in fiber density, local "filling," and variations in pores or interfibrillar spaces (Xiao *et al.,* 2025). Within this framework, the fact that vegetable treatments exhibited all features (particle pore crack fiber) can be interpreted as an indication that these vegetable agents function not only as colorants but also interact intensely with the collagen matrix, resulting in morphological markers that are more comprehensive and defined compared to the control. The control's lack of a "fiber" panel (no result) may practically relate to limitations in image quality or sample conductivity, preparation conditions, or a surface structure that is less "readable" under specific observation modes, rather than being solely a chemical effect (Hassan *et al*., 2023).

The correlation between pores/cracks and mechanical performance is aligned with the literature: large or open pores and micro cracks act as stress concentration sites that facilitate the initiation and propagation of damage during tensile or tear loading, whereas a more organized fiber network and more uniform porosity tend to support better stress distribution. The SEM studies on leather (including vegetable tanned leather) demonstrate that microstructural changes such as increased damage or cracking at the fibril level correlate with a decline in mechanical resistance and structural stability under specific treatments or environments (Vyskočilová et al., 2022).

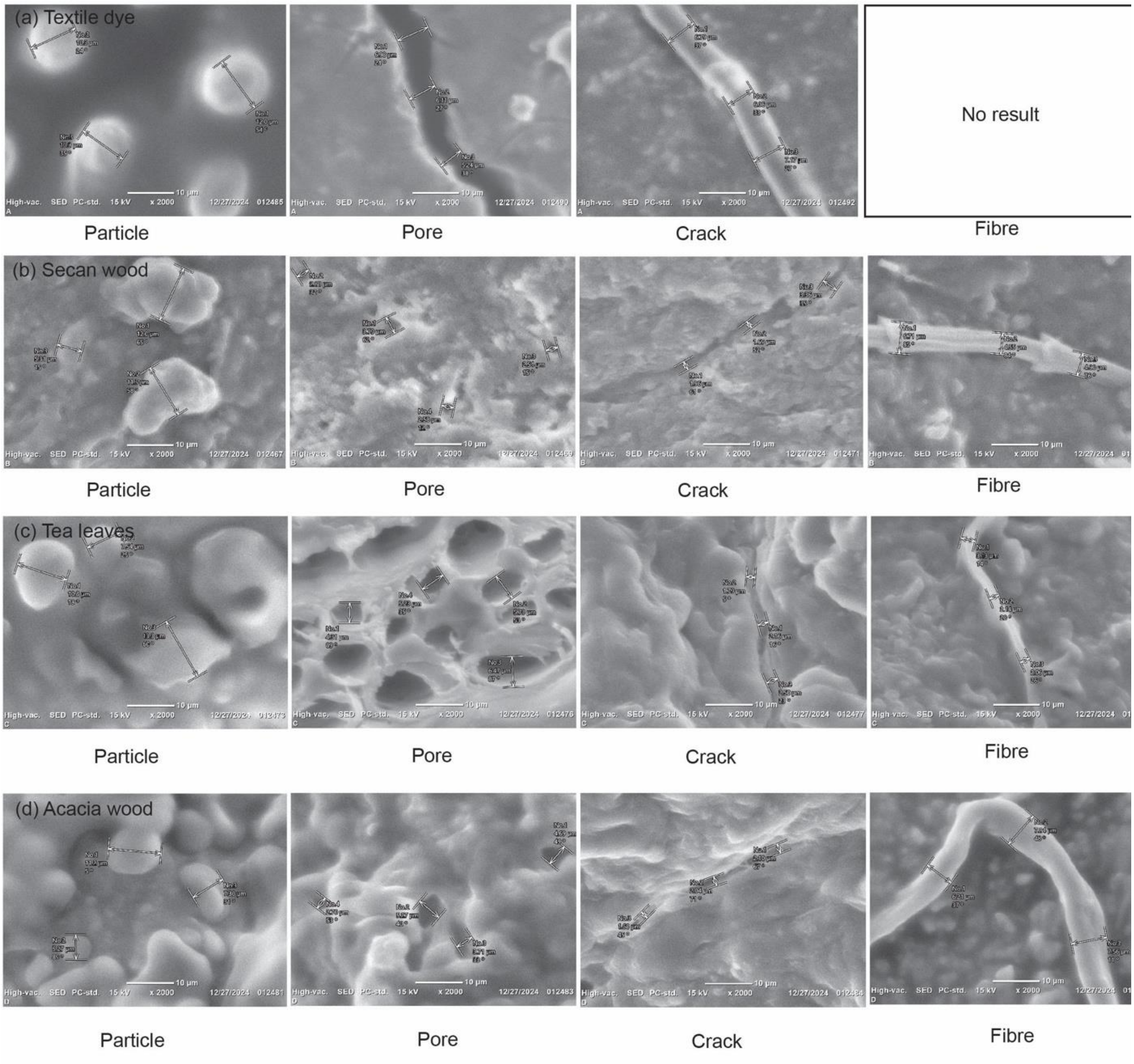

Figure 3. SEM micrographs of tanned chicken feet skin under various treatments

Note : Rows represent the treatments: (a) control/textile dye, (b) Sappan wood, (c) tea leaves, and (d) Acacia wood. Columns represent the observation categories: particles, pores, cracks, and fibers. For the control treatment, the "fiber" panel was not obtaine (no result).

Description: The micrographs were utilized for the qualitative evaluation of the collagen matrix configuration (porosity, cracks, and fiber features) to serve as a basis for interpreting the differences in mechanical properties among the treatments.

Specifically for chicken feet based materials, collagen characterization studies on chicken feet skin have also reported the use of SEM to assess morphology and structural integrity, reinforcing that the SEM approach is indeed relevant for explaining variations in the properties of collagen based materials (Zourazema *et al.*, 2025). Consequently, the discrepancy in porosity (e.g., pores appearing more open in certain treatments) and the variations in cracking among treatments provide a plausible mechanistic basis to explain why deformation responses and tear/tensile resistance in this study do not always follow a linear trend. Instead, they are determined by a combination of fiber packing, matrix continuity, and the presence of micro defects (Sadowski *et al*., 2017).

CONCLUSION

This study demonstrates that broiler chicken feet skin holds significant potential as a premium value alternative leather material through an eco-friendly tanning approach utilizing local vegetable agents, as the choice of tanning agent was proven to consistently modulate physical mechanical characteristics, macroscopic appearance, and tissue microstructure. The protein dominated (collagenous) composition of the raw material provides a reactive substrate for cross link formation, while variations in weight and thickness following the tanning process indicate differences in retention and filling effects associated with drying behavior and fiber compaction. Mechanically, the tensile elongation tear responses exhibit a reinforcement deformability trade off among the agents, further supported by SEM analysis through variations in porosity and cracking as indicators of stress concentration sites. Simultaneously, macroscopic observations of differences in color and surface homogeneity confirm that the tanning agent also determines the aesthetic quality and grain/scale pattern definition crucial for the premium segment. Overall, these findings provide a scientific and practical foundation for a local resource-based waste to resource strategy to convert chicken feet waste into more sustainable alternative leather materials.

SUGESTION

Furthermore, this study serves as a basis for subsequent optimization (e.g., extract concentration, pH, and fixation time) to achieve a more optimal balance of functional performance and aesthetics.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Directorate of Islamic Higher Education, Directorate General of Islamic Education, Ministry of Religious Affairs of the Republic of Indonesia, for the financial support provided through the Litapdimas research grant program 2024. Appreciation is also extended to Universitas Islam Negeri Alauddin Makassar for the institutional support and facilities provided during this study.

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