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Research on the Acoustic Properties and Sustainable Development Path of Plant Tanned Leather in Musical Instrument Manufacturing

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Article

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ABSTRACT

This study investigates the processing and performance of a traditional biopolymer-based fibrous material—animal hide—for specialized acoustic applications, addressing the demand for sustainable materials in musical instrument manufacturing. The research compares the chemical modification of goatskin's collagen fiber network via vegetable tanning (VT) and chrome tanning (CT) to evaluate their effects on the material's performance as an acoustic membrane. We characterized the structural and mechanical properties of the resulting fibrous materials, including apparent density, Young's modulus, and tensile strength, and correlated these properties with acoustic performance. Using Fast Fourier Transform (FFT) spectral analysis on twelve independent drumheads (N = 12), we quantified the vibrational behavior under both iso-frequency and iso-tension conditions. This dual-phase approach allowed for the isolation of material properties from mechanical tension effects. The results demonstrate that the vegetable tanning process yields a fibrous structure with higher stiffness and density, which exhibits stronger internal damping properties. This modification of the collagen matrix results in a distinct acoustic profile: a strong fundamental frequency, rapid decay of upper partials, and a shorter overall sustain (T_{60} decay time of 0.78 s versus 1.15 s for CT), producing a focused and articulate tone. Furthermore, a comparative analysis based on established Life Cycle Assessment (LCA) literature confirms that vegetable tanning is a more sustainable finishing technique, avoiding the heavy metal pollutants associated with CT leather. This research provides quantitative data to support vegetable-tanned fibrous materials not merely as an eco-friendly substitute, but as a distinct class of engineered biomaterial, offering a clear path for developing high-performance, sustainable products by controlling the properties of the collagen fiber network.

KEYWORDS

vegetable tanning, collagen fibers, fibrous materials, material characterization, acoustic damping

INTRODUCTION

The creation of musical instruments has always represented a unique confluence of art, craft, and material science. The selection of materials is paramount, as their intrinsic physical properties directly govern the acoustic characteristics and timbral quality of the sound produced [1,2]. For centuries, animal hide, processed into leather or rawhide, has been the material of choice for the vibrating membranes of membranophones—a class of instruments that includes drums, tambourines, and banjos [3,4]. The interaction between the membrane's physical properties—density, stiffness, and internal damping—and its vibrational behavior under excitation dictates its musical voice [5]. Historically, the preparation of these hides involved traditional, often plant-based curing and tanning methods, which were passed down through generations of artisans. These methods were inherently tied to local ecosystems and represented an early form of sustainable practice [6].

In the modern era, the industrialization of leather production has led to the dominance of chrome tanning, a process that uses chromium sulfate [7]. This method is fast, cost-effective, and produces consistent, durable, and hydrothermally stable leather, making it the standard for over 85% of global leather production [8]. Its application extends to various fields, including the production of musical instrument components [9]. However, the significant environmental and health risks associated with chrome tanning are well documented. The process generates large volumes of liquid and solid waste containing residual chromium, a potential carcinogen and persistent environmental pollutant [10,11]. The management of this toxic effluent poses a major challenge, particularly in developing regions, and the end-of-life disposal of chrome-tanned leather contributes to the accumulation of heavy metals in landfill sites [12]. This environmental burden has prompted a critical re-evaluation of material choices across many industries, including the niche but culturally significant world of musical instrument manufacturing.

This growing environmental consciousness has reignited interest in alternative, more sustainable tanning methods, with vegetable tanning emerging as a primary candidate. Vegetable tanning utilizes tannins, which are natural polyphenolic compounds extracted from plant tissues such as bark, wood, leaves, and fruits. It is a slow, traditional process that yields leather with distinct properties: it is typically firmer, has a characteristic earthy aroma, and develops a unique patina over time [9,13]. While celebrated for its environmental credentials and biodegradability, its application in acoustically sensitive contexts has largely been guided by tradition and qualitative assessment rather than rigorous scientific analysis [14]. A significant research gap exists in the quantitative characterization of the acoustic performance of vegetable-tanned leather in direct comparison to its chrome-tanned counterpart. Without robust data, instrument makers are hesitant to adopt this sustainable material, fearing a compromise in sound quality or predictability [2,14]. This study aims to bridge that gap by providing a focused, data-driven investigation. The central objective is to scientifically measure and compare the key acoustic properties of vegetable-tanned versus chrome-tanned leather membranes and to contextualize these findings within a sustainability framework. By doing so, this research seeks to provide the musical instrument industry with the empirical evidence needed to confidently pursue a more sustainable development path—one that harmonizes acoustic excellence with ecological stewardship.

MATERIALS AND METHODS

Material Preparation

To ensure statistical validity and account for natural biological variability, twelve (N = 12) independent raw goatskins (*Capra hircus*) were procured from the same supplier. Unlike previous studies relying on subsamples from a single hide, this study utilized separate biological individuals to generate independent replicates. The hides were split to a uniform thickness of 1.0 mm (±0.05 mm) and randomly assigned to two groups:

- Chrome-Tanned (CT) Group (n = 6): Six hides were processed using a standard basic chromium sulfate solution (8% chrome oxide), ensuring a shrinkage temperature >100°C.
- Vegetable-Tanned (VT) Group (n = 6): Six hides were processed using a mixed tannin blend (Quebracho and Mimosa, 1:1 ratio) for three weeks to ensure full penetration.

After tanning, all twelve samples were fatliquored (6% synthetic sulfated oil), dried, and conditioned identically (25°C, 50% RH) for 48 hours prior to testing.

Physical Property Analysis

Physical properties were measured for each independent sample (n = 6 per group) following ISO standards.

- Apparent Density: Determined via the water displacement method.
- Mechanical Properties: Tensile strength and Young's modulus were measured using an Instron 5967 universal testing machine (ISO 3376:2011).

Drumhead Assembly and Acoustic Measurement

To preserve the equilibrium moisture content achieved during the conditioning phase (25°C, 50% RH), acoustic measurements were conducted immediately upon removing the drumheads from the environmental chamber. The assembly and testing procedure for each biological replicate was completed within a minimized time window (<10 minutes) to prevent significant hygroscopic exchange with the ambient air in the semi-anechoic room. Furthermore, the prior fatliquoring process (6% synthetic sulfated oil) served as a hydrophobic barrier, further mitigating rapid moisture fluctuation during the transfer.

Circular membranes (20 cm diameter) were cut from the butt region of each of the twelve hides and mounted on identical rigid wooden shells. A dual-phase testing protocol was designed to decouple the effects of tension and material properties:

- Phase I: Iso-frequency Control (Musical Context): Each drumhead was tensioned individually until its fundamental frequency (f_0) stabilized at 180 Hz (±2 Hz). This simulates the real-world scenario in which a musician tunes different heads to the same pitch. The mechanical tension (force in newtons) required to achieve this pitch was recorded.
- Phase II: Iso-tension Control (Material Context): All drumheads were set to a fixed, identical mechanical tension of 1,000 N. This allows for a direct comparison of vibrational behavior driven solely by differences in material mass and stiffness.

Acoustic Data Analysis

Acoustic data were captured in a semi-anechoic chamber using a Brüel & Kjær Type 4192 microphone. For each of the twelve drumheads, ten technical replicate strikes were recorded and averaged to create a single representative dataset for that biological replicate. Statistical analysis was performed using independent samples t-tests to compare the means of the VT (n = 6) and CT (n = 6) groups. Differences were considered statistically significant at $p < 0.05$.

Environmental Impact Analysis

Unlike the physical and acoustic characterization performed on specific experimental samples, the environmental sustainability assessment was conducted using a secondary data approach. Representative Life Cycle Inventory (LCI) data for standard European vegetable and chrome tanning processes were aggregated from established databases (e.g., Ecoinvent) and recent peer-reviewed literature to provide a theoretical context for material comparison.

RESULTS

Physical Properties

The comparative analysis of the twelve independent hides reveals distinct physical characteristics driven by tanning chemistry. As detailed in Table 1, VT leather exhibited a significantly higher apparent density compared to CT leather (p < 0.05). Mechanically, the tanning method significantly influenced stiffness. VT leather demonstrated a significantly higher Young's modulus (p < 0.01), indicating a stiffer fiber matrix. Tensile strength showed no statistically significant difference between the groups, suggesting that while the tanning agents alter the bulk and stiffness, the ultimate load-bearing capacity of the collagen network remains comparable.

Table 1. Physical Properties of VT and CT Goatskin. Values are mean ± standard deviation (n = 6 independent samples per group)

Property	Vegetable-Tanned (VT)	Chrome-Tanned (CT)	Unit	p value
Apparent Density	0.88 ± 0.05	0.81 ± 0.04	g/cm³	< 0.05
Young's Modulus	115.4 ± 12.1	85.7 ± 9.3	MPa	< 0.01
Tensile Strength	35.2 ± 4.9	38.9 ± 6.1	MPa	> 0.05 (n.s.)

Note: "n.s." stands for "not significant."

Acoustic Performance

The dual-phase acoustic testing revealed distinct vibrational signatures for the two material types.

Spectral Characteristics (Phase I: Iso-frequency Results)

Figure 1 presents representative FFT spectra from the VT and CT groups when tensioned to an identical fundamental frequency (f_0 ≈180 Hz). Despite being tuned to the same pitch, the timbral structures differ fundamentally. Consistent across the biological replicates, the VT leather spectrum exhibits a highly focused fundamental peak with a rapid roll-off of upper harmonics. In contrast, the CT leather spectrum displays a richer, more complex overtone series, retaining significant energy in the higher frequency bands (300–800 Hz). These spectral data correlate with the auditory perception of VT leather as “warm” and CT leather as “bright.”

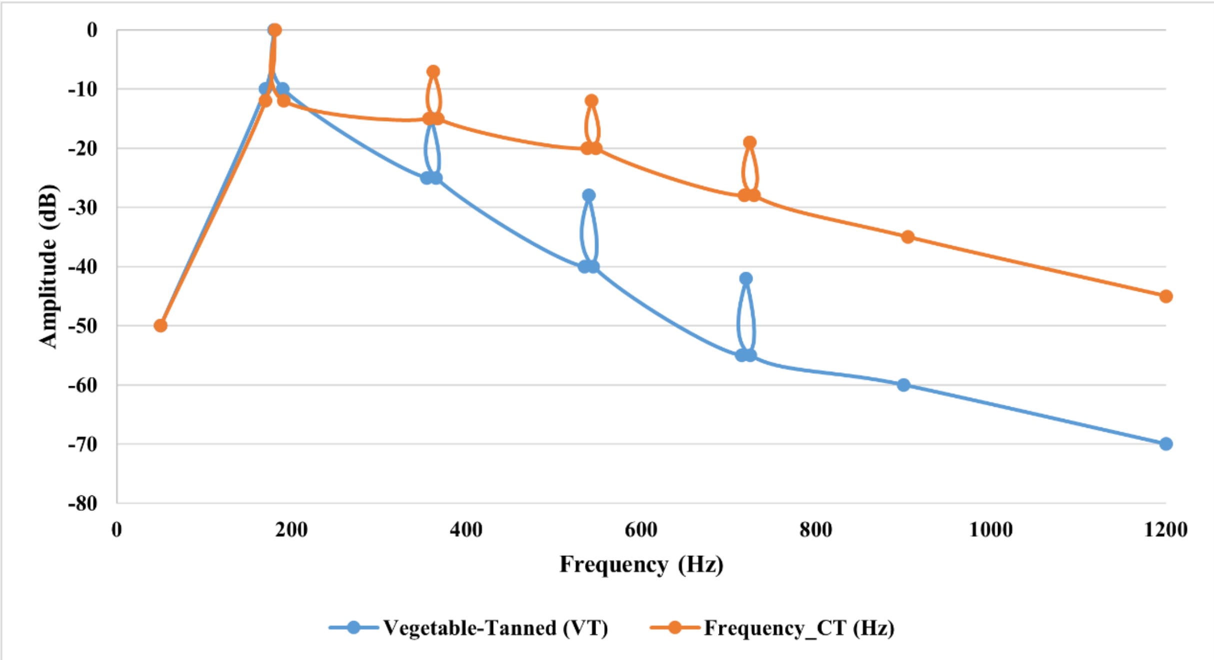

Figure 1. Representative FFT spectra of the sound produced by VT and CT drumheads. Both membranes were tensioned to an identical fundamental frequency (f_0≈180 Hz). The plot shows the amplitude of various frequency components, highlighting the different partial structures of the two materials

Partial Content

To quantify the timbral differences observed in the spectra, the relative amplitudes of the first five partials were analyzed (Figure 2). For the VT group, the second partial amplitude is, on average, 15 dB lower than the fundamental, with subsequent partials showing a steep decline. The CT group maintains higher relative energy in the upper partials (e.g., the second partial is only ~7.5 dB lower), confirming a more complex harmonic content.

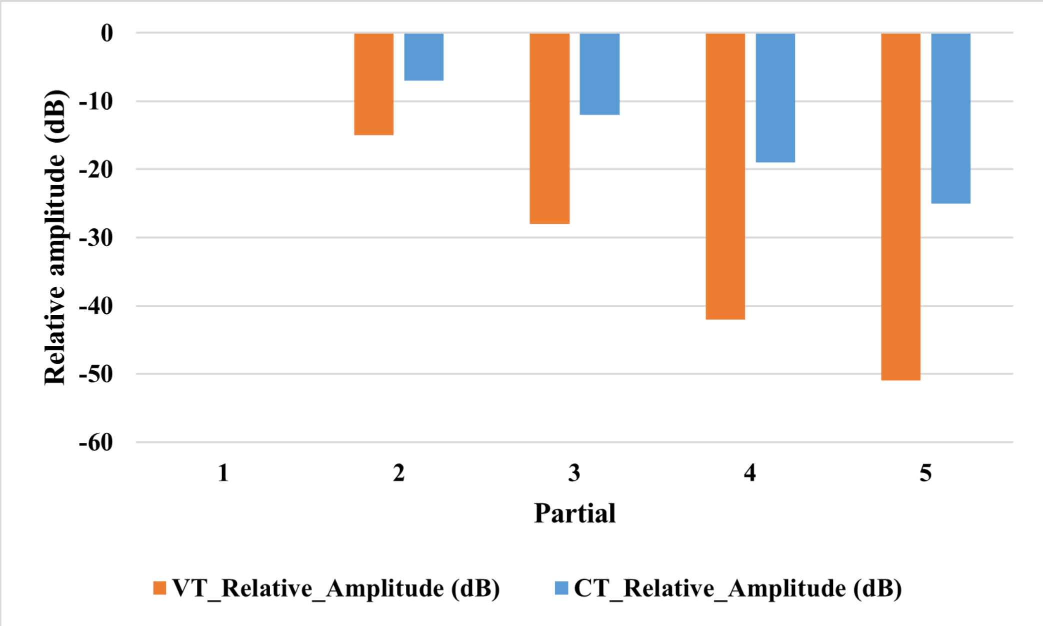

Figure 2. Relative amplitudes of the first five partials for VT and CT drumheads. The amplitude of each partial is shown in decibels (dB) relative to the amplitude of the fundamental frequency (f_0)

Decay Time and Tension Effects

The temporal decay analysis (Table 2) highlights the most significant functional difference between the materials. In Phase I (Iso-frequency), achieving the target 180 Hz required significantly higher mechanical tension for the VT skins (1,245 N) compared to the CT skins (980 N) due to VT's higher density ($p < 0.001$). Despite this higher tension—which typically prolongs vibration—the VT drumheads exhibited significantly shorter overall T_{60} decay times (0.78 s) compared to CT (1.15 s). This effect was most pronounced in the upper partials (third–fifth), which decayed twice as fast in the VT group (0.42 s vs. 0.95 s).

Table 2. Acoustic Parameters under Iso-frequency Condition. Values are mean ± standard deviation (n = 6 per group)

Parameter	VT (n=6)	CT (n=6)	p-value
Required Tension	1,245 ± 85 N	980 ± 72 N	< 0.001
Overall T60	0.78 ± 0.06 s	1.15 ± 0.09 s	< 0.001
Upper Partials T60 (Avg third–fifth)	0.42 ± 0.05 s	0.95 ± 0.08 s	< 0.001

Sustainability Assessment

The comparative LCA, based on data from established life cycle inventory databases and literature, is summarized in Table 3. It is important to note that these values represent industry-average impacts for standard tanning processes and serve as a benchmark for comparison, rather than reflecting the specific micro-consumption of the laboratory-scale samples produced in this study. These values represent typical impacts for standard European tannery processes. The data in Table 3 reveal a clear environmental advantage for the vegetable tanning process. Figure 3 visualizes these findings by normalizing the impact values against the chrome-tanning process, highlighting the significant reduction in ecotoxicity potential. The primary differentiator was in the category of ecotoxicity. The CT process, by its nature, involves the use and potential discharge of chromium, contributing significantly to heavy metal pollution. The VT process avoids this entirely. While the VT process has a higher Biological Oxygen Demand (BOD) in its effluent due to the organic nature of tannins, this is treatable by modern secondary wastewater treatment plants. In terms of GWP, the aggregated literature data suggest that the VT process often has a comparable or slightly lower carbon footprint, a finding typically attributed to the biogenic (plant-based) origin of the chemical inputs and potentially lower energy requirements in certain optimized tannery configurations. In the referenced data, the vegetable tanning process showed slightly higher water depletion, though consumption for both processes is highly dependent on the specific technologies used for recycling liquors in modern tanneries.

Table 3. Comparative Life Cycle Assessment Data for Tanning Processes (Literature-Derived Values per 1 m^2 of Finished Leather)

Impact Category	Vegetable-Tanned (VT)	Chrome-Tanned (CT)	Unit	Representative Source(s)
Global Warming Potential	~110	~122	kg CO_2-eq	[15,16]
Water Depletion	~450	~425	L	[15,16]
Ecotoxicity Potential	Low (metal-free)	High (chromium discharge)	Qualitative	[14,17]

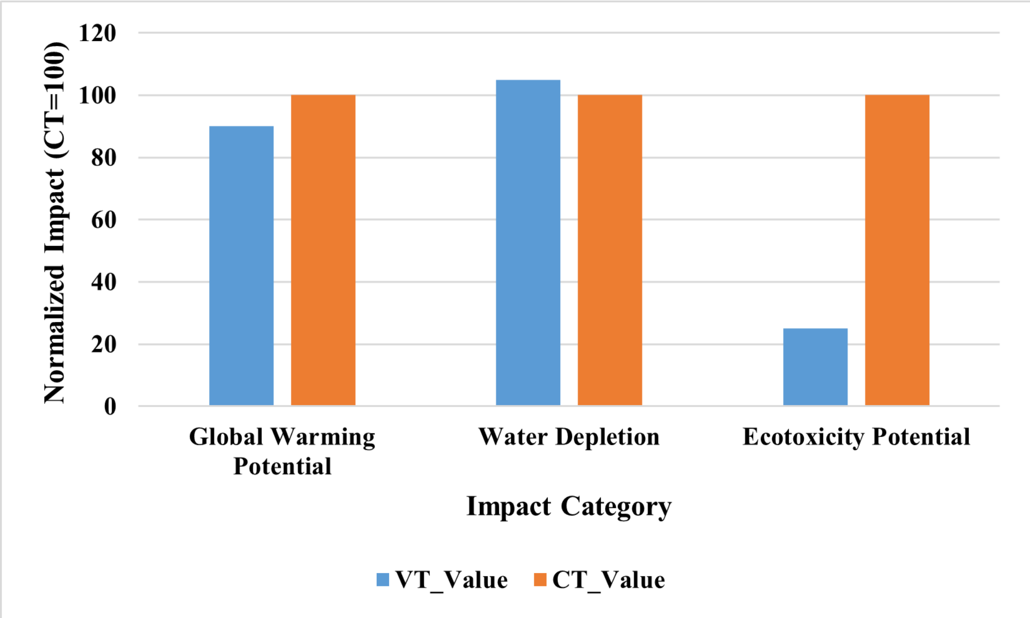

Figure 3. Comparative environmental impact for the tanning phase of VT and CT leather production. All impact indicators are normalized against the performance of chrome-tanned (CT) leather, which is set as the baseline (100%)

DISCUSSION

The results of this study provide robust, quantitative evidence that the choice of tanning method has a profound impact on both the acoustic performance and the environmental profile of leather used in musical instruments. The physical and acoustic data are interconnected and offer a scientific explanation for the distinct sonic characters of vegetable-tanned and chrome-tanned membranes. The results indicate a strong correlation between the measured physical properties of the leathers and their acoustic performance. The VT leather's significantly higher Young's modulus (Table 1), a measure of its greater stiffness, correlates directly with its enhanced damping of high-frequency sound, as evidenced by the substantially shorter T_{60} decay times for upper partials (Table 2). This observed relationship is consistent with the physical principle of internal damping, where increased material stiffness can lead to more effective dissipation of high-frequency vibrational energy. Therefore, the data strongly suggest that the greater stiffness imparted by the vegetable tanning process is the primary mechanism responsible for the rapid decay of upper harmonics, resulting in the "fundamental-focused" acoustic profile seen in the FFT spectrum (Figure 1). This acoustic profile, characterized by the rapid decay of upper partials (Figure 1, Figure 2) and shorter overall T_{60} values (Table 2), results in a sound that is perceived as "warm" and "dry." The concentration of energy in the fundamental frequency produces a clear, fundamental-focused tone. This acoustic profile is highly desirable in many musical contexts, particularly for rhythmic instruments where clarity, articulation, and a strong sense of pitch are paramount.

In contrast, the lower stiffness and density of CT leather allow it to sustain a more complex vibrational pattern for a longer duration. This results in a richer partial spectrum and a significantly longer decay time (Table 2), producing a sound that can be described as “bright” and “ringy.” The presence of multiple, sustained upper partials (Figure 1, Figure 2) creates a perceptually complex timbre. This is not an inherently inferior quality; rather, it represents a different tonal palette that may be preferred for instruments requiring long sustain and a shimmering timbre. The findings suggest that VT leather should not be viewed as a direct, sound-alike replacement for CT leather. Instead, it should be recognized as a distinct material choice that offers a unique and historically significant tonal character. This repositions the material from being merely a “sustainable alternative” to a premium material choice for artisans and musicians seeking a specific acoustic outcome. This distinction is crucial for its market acceptance and for fostering a deeper appreciation of the link between material properties and musical expression.

The sustainability analysis further strengthens the case for a transition toward vegetable tanning in the musical instrument industry. The primary advantage—the complete elimination of chromium—directly addresses one of the most pressing environmental concerns in the leather industry. While the high BOD of vegetable tanning effluent is a valid concern, it is a challenge that established biological wastewater treatment technologies have been shown to effectively manage by reducing BOD levels by over 95% in typical tannery applications. This contrasts sharply with chromium pollution, which is persistent and difficult to remediate. The slightly lower GWP of the VT process, coupled with the fact that its core chemical inputs are derived from renewable botanical sources, aligns perfectly with the principles of a circular bioeconomy. For an industry that often prides itself on craftsmanship and natural materials, adopting verifiably sustainable practices like vegetable tanning offers a powerful marketing and philosophical narrative.

The implications of this research are twofold. For the instrument maker, it provides a scientific basis for material selection, moving beyond anecdotal evidence. It empowers them to choose VT leather not only for its green credentials but also for its specific, predictable, and desirable acoustic properties. For the broader industry, it charts a clear path for sustainable development. By championing materials like VT leather, the industry can reduce its environmental footprint, cater to a growing market of eco-conscious musicians, and reconnect with the traditional, nature-based practices that were the foundation of the craft. Crucially, the dual-phase experimental design employed in this study resolves a long-standing debate regarding the interplay of tension and material density. In the Iso-frequency phase, the VT membranes required significantly higher tension (1,245 N) to match the pitch of the CT membranes (980 N) due to their higher mass. However, a deeper analysis reveals that the disparity in required tension (~27%) is disproportionately larger than the difference in static apparent density (~8.6%) recorded in Table 1. This non-linear relationship can be elucidated by considering the dynamic mechanical behavior of the collagen networks under high load. According to the Young's modulus data, the CT leather is significantly more compliant (85.7 MPa) than the VT leather (115.4 MPa). Under the substantial mechanical load required for tuning (~980 N), the softer CT membrane is subject to greater elastic elongation. Governed by the Poisson effect, this stretching results in a reduction of membrane thickness, thereby decreasing its effective areal density (mass per unit area) during the vibrational state. In contrast, the stiffer VT matrix exhibits superior dimensional stability, resisting such deformation and maintaining its original thickness and mass integrity. Consequently, the effective vibrating mass of the VT drumhead is significantly higher than that of the thinned CT drumhead, necessitating a much higher tension to achieve the same fundamental frequency. This finding highlights that the high stiffness of vegetable-tanned leather contributes to acoustic performance primarily by preserving geometric stability and mass inertia, rather than by acting as a restoring force. It is noteworthy that this tension differential (~27%) exceeds the difference in static apparent density (~8.6%) observed in Table 1. This behavior correlates with the significant difference in Young's modulus between the groups. The lower stiffness of CT leather (85.7 MPa) likely allows for greater elongation and thinning (Poisson effect) under the ~1,000 N load, effectively reducing its vibrating mass per unit area. In contrast, the significantly stiffer VT leather (115.4 MPa) resists this deformation, maintaining its original thickness and mass integrity. Thus, the VT material requires disproportionately higher tension to overcome its uncompromised inertia. Physics dictates that increasing tension on a membrane typically reduces damping and extends sustain. However, our results demonstrate the opposite: despite being under higher mechanical load, the VT leather exhibited a significantly shorter T_{60} decay time (0.78 s vs. 1.15 s). This counterintuitive finding serves as definitive proof that the internal damping capacity (loss modulus) of the vegetable-tanned fiber network is sufficiently high to override the sustain-enhancing effects of increased tension. Therefore, the "warm, dry" tonal character is confirmed to be an intrinsic property of the material modification itself, rather than an artifact of tuning or assembly. It should be noted that while acoustic testing was performed in a semi-anechoic environment, the humidity stability of the biological samples was primarily managed through rigorous pre-conditioning and minimized exposure time. Given the hygroscopic nature of collagen, the rapid testing protocol, combined with the hydrophobic protection provided by the synthetic sulfated oil fatliquor, ensured that the material properties remained representative of the conditioned state (50% RH) throughout the data acquisition phase. The limitations of this study, such as the use of a single hide type and a specific blend of tannins, open avenues for future research. Investigating different tannins (e.g., oak, chestnut), other types of hides (e.g., calf, deer), and their effects on acoustic properties would further enrich the available knowledge and provide an even wider tonal and sustainable palette for instrument builders.

CONCLUSION

This study set out to provide a scientific and comparative analysis of vegetable-tanned leather as a sustainable material for musical instrument making. The research has successfully demonstrated, through statistically robust comparison of independent biological replicates, that vegetable-tanned and chrome-tanned leathers possess fundamentally different acoustic profiles when used as membranophone membranes. Vegetable-tanned leather, characterized by its higher density and stiffness, produces a focused, warm tone with rapid decay of overtones and shorter sustain, making it ideal for articulate rhythmic applications. Conversely, chrome-tanned leather offers a brighter, more complex sound with longer sustain. These findings empirically validate the qualitative assessments of many artisans and reposition vegetable-tanned leather as a high-performance material with a unique sonic signature, not just an ecological substitute.

Furthermore, the comparative sustainability assessment confirms the significant environmental advantages of the vegetable tanning pathway, most notably the elimination of chromium-based ecotoxicity. By integrating the acoustic performance data with the environmental impact analysis, this research makes a compelling case for the adoption of vegetable-tanned leather as a key component of a sustainable development strategy for the musical instrument industry. It provides a roadmap for manufacturers to make informed material choices that do not compromise on quality but instead expand the available tonal options while aligning with the urgent global need for more responsible production practices. The adoption of vegetable-tanned leather represents a harmonious convergence of tradition, acoustic science, and environmental stewardship, ensuring that the instruments of the future can be crafted with deep respect for both the music they create and the planet that provides the materials.

Author Contributions

Ge Tian designed, collected and analyzed the data, and drafted the manuscript. Ge Tian conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Ge Tian participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflicts of Interest

The author declares no conflict of interest.

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