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Anatomical and Structural Characterization of Ghanaian Indigenous Vegetable-Tanned Leathers for Laser Engraving and Cutting

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Abstract
This study investigated the anatomical and structural characteristics of Ghanaian Indigenous Vegetable-Tanned Leathers (GIVTLs) and evaluated their suitability for laser engraving and cutting. Although digital fabrication technologies are increasingly used in art, design, and material-processing environments, limited empirical evidence explains how indigenous vegetable-tanned leathers respond to laser exposure. Thirty samples of vegetable-tanned goat-skins obtained from traditional tanneries in Kumasi, Tamale, and Bolgatanga were categorized into four anatomical zones: bend, shoulder, belly, and neck. Using adapted ISO/ASTM-aligned procedures, the study assessed thickness, moisture content, macro-grain structure, and mechanical integrity of the

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selected leathers. Results showed that the bend zone had the highest dimensional stability, lowest moisture content, compact grain structure, and strongest mechanical cohesion, making it the most suitable zone for diode-laser processing. The shoulder demonstrated moderate suitability, whereas the belly and neck recorded higher moisture levels, irregular thickness, porous grain structures, and weak structural cohesion. These conditions increased the likelihood of inconsistent engraving, darkening, and poor edge quality. Interpreted through laser-material interaction theory and structure-property relationships, the findings demonstrate that collagen density, moisture gradients, and grain compactness influence heat diffusion, energy absorption, and ablation behaviour. The study provides material-centred evidence for zone-specific parameter selection and supports the development of localized guidelines for precision laser processing of GIVTLs.

1. Introduction

Ghanaian Indigenous Vegetable-Tanned Leathers (GIVTLs) occupy an important place in Ghana's cultural economy, craft heritage, and leather-product development. They are produced through community-based tanning systems that rely on botanical tannins, hand-processing, and open-air drying. These practices preserve local knowledge but also create material variability that can influence performance during modern digital fabrication processes (Appiah-Brempong et al., 2020; Covington & Wise, 2019).

The growing interest of diode-laser engraving and cutting in art, design, and leather-technology training environments, including the Department of Integrated Art and Technology at KNUST, requires valid knowledge of how indigenous leathers behave under controlled laser exposure. Unlike industrially processed chrome-tanned leathers, GIVTLs are not fully standardized. Their bend, shoulder, belly, and neck zones differ in thickness, moisture content, grain compactness, collagen arrangement, and mechanical strength. These differences affect focal depth, thermal diffusion, energy absorption, ablation, engraving clarity, kerf formation, and edge quality (Gulbinienė et al., 2022; Steen & Mazumder, 2010).

Despite increasing access to laser machines in Ghana, empirical data on the material behaviour of indigenous vegetable-tanned leathers remain limited; resulting in students, instructors, artisans, and private laser operators often relying on trial-and-error settings originally developed for synthetic or industrial leathers. Such practice may cause over-burning, poor engraving contrast, incomplete cutting, and material waste. The purpose of this study therefore, was to characterize the anatomical and structural properties of GIVTLs and determine how zone-specific material differences may inform precision laser engraving and cutting results.

The conceptual and theoretical anchoring for this study is presented in Figure 1. The diagram shows how laser–material interaction theory, structure–property relationship theory, and materials processing and characterization literature jointly frame the analysis of GIVTLs. It provides the basis for understanding how anatomical features such as thickness, moisture content, fibre arrangement, grain compactness, and dimensional stability influence the suitability of Ghanaian Indigenous Vegetable-Tanned Leathers for laser engraving and cutting.

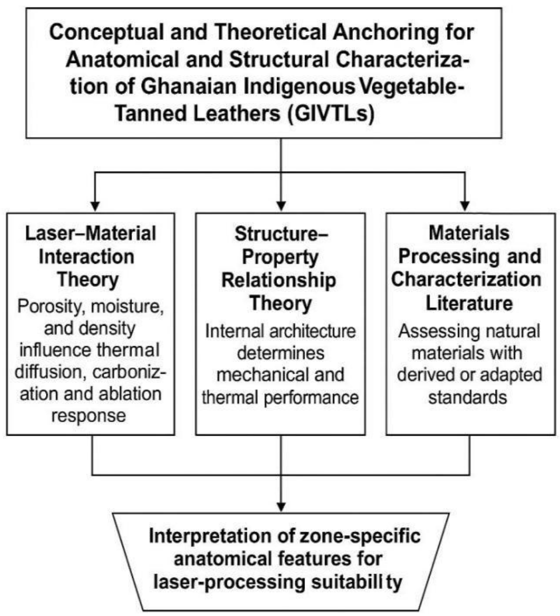

Figure 1: Conceptual and Theoretical Anchoring for Anatomical and Structural Characterization of Ghanaian Indigenous Vegetable-Tanned Leathers (GIVTLs).

2. Literature review

2.0 Overview

This section reviews literature on indigenous vegetable-tanned leather, anatomical variability, laser–material interaction, and structure–property relationships to establish the scientific basis for analysing how GIVTL zones respond to laser engraving and cutting.

2.1 Indigenous Vegetable-Tanned Leather and Anatomical Variability

Vegetable tanning is a collagen-stabilizing process in which plant-derived tannins bind to hide fibres to produce leather with characteristic firmness, colour, and durability. In artisanal African tanning contexts, tanning outcomes are strongly affected by hide source, botanical materials, soaking, liming or dehairing methods, stretching, drying conditions, and finishing practices (Boateng et al., 2021; Yapi et al., 2022). These factors make indigenous leathers culturally valuable but structurally variable.

Leather is not anatomically uniform. The bend commonly has dense, well-aligned collagen bundles and fewer wrinkles; the shoulder tends to be moderately stable; while the belly and neck usually show looser fibre networks, higher wrinkle density, variable thickness, and weaker mechanical cohesion. Such zone-based differences are widely recognized in leather science because they influence tensile behaviour, surface finishing, dimensional stability, and processing performance (Mihai et al., 2022; Sharmin et al., 2021).

2.2 Laser-Material Interaction in Collagen-Based Materials

Laser processing involves the interaction of concentrated optical energy with a material surface. In organic collagen-based materials such as leather, the absorbed energy produces heating, dehydration, carbonization, ablation, and sometimes structural weakening, depending on the material properties and laser parameters used (Steen & Mazumder, 2010; Shakil et al., 2023).

Moisture content, density, surface morphology, and thickness uniformity are particularly important. Materials with stable thickness and compact grain structures tend to absorb and dissipate heat more predictably, whereas porous or moisture-rich surfaces may produce irregular darkening, uneven engraving depth, smoke, and rough edges (Hu et al., 2020; Li & Chen, 2018). For leather, these principles suggest that anatomical zoning should be considered before selecting laser power, speed, and number of passes for engraving and cutting related activities.

2.3 Structure-Property Relationships and Laser Processing Suitability

The structure-property relationship perspective explains that material performance depends on internal architecture. In leather, collagen density, fibre orientation, pore distribution, and moisture gradients determine strength, dimensional stability, surface response, and thermal behaviour (Callister & Rethwisch, 2020; Zhang et al., 2021). Compact collagen networks may support cleaner engraving and cutting, while weak or irregular networks may deform, char, or tear under laser energy.

This study therefore, connects leather anatomy, material characterization, and laser-processing behaviour. Examining the bend, shoulder, belly, and neck zones separately, provides a scientific basis for selecting suitable areas of GIVTLs for instructional, creative, and production-based laser applications.

Conclusion

The reviewed literature shows that the laser-processing performance of Ghanaian Indigenous Vegetable-Tanned Leathers is strongly influenced by anatomical variation, collagen structure, moisture content, grain compactness, and mechanical stability. It establishes that effective laser engraving and cutting require a clear understanding of leather material behaviour, especially across the bend, shoulder, belly, and neck zones. Therefore, anatomical and structural characterization provides a necessary foundation for selecting suitable leather zones and developing reliable laser-processing guidelines specifically for engraving and or cutting GIVTLs.

3. Methodology

3.0 Overview

This section outlines the procedures used to select, prepare, zone, measure, and analyse Ghanaian Indigenous Vegetable-Tanned Leathers for laser-processing suitability.

3.1 Research Design

A descriptive laboratory-based anatomical profiling design was employed to document natural structural variations across the anatomical zones of GIVTLs. This design was appropriate because the study examined inherent material variability without experimentally manipulating the leather before characterization (Mihai et al., 2022).

3.2 Study Sites and Sample Source

Freshly tanned goat leathers were sourced from three major indigenous tanning centres in Ghana; namely, Kumasi in the Ashanti Region, Tamale in the Northern Region, and Bolgatanga in the Upper East Region. These sites represent important vegetable-tanning ecosystems characterized by botanical tannins, hand-processing, manual stretching, and open-air drying techniques (Boateng et al., 2021; Yapi et al., 2022). Figure 2 A and B depicts a Cross-section of the Tamale Zongo Lane traditional tannery.

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A) Tamale Zongo Lane traditional tannery.	B) Researcher at the tannery site.

Figure 2A & B: Cross-section of the Tamale Zongo Lane traditional tannery. Photograph by Victor Boateng-Nimoh, Temale, April 2024.

3.3 Sampling Procedure

Purposive sampling was used to obtain 30 structurally sound goat leathers by physically observing them; with 10 samples from each region. Selection was done jointly with experienced artisanal tanners who assisted in identifying hides with relatively uniform tanning and minimal structural defects. Leathers with bacterial scars, incomplete tanning, excessive wrinkles, or major surface defects were excluded to improve the reliability of anatomical comparisons.

A) Selected dyed leather without major defects.	B) Undyed leather selected for comparison.

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Figure 3A & B: Sample leathers without major defects selected for the study. Photograph by Victor Boateng-Nimoh, Temale, April 2024

3.4 Sample Preparation and Conditioning

All 30 selected leathers underwent routine post-tanning preparation, including light sanding, soaking, soaping, stretching, and drying. (Refer to **Figure 4).** These steps reflected real-world Ghanaian tannery procedures and ensured that the material examined matched the leather commonly used by artisans and students. Prepared hides were conditioned at 25 ± 2°C and 50 ± 5% relative humidity for 72 hours following ISO 2419:2024-aligned procedures. Conditioning stabilized material moisture and reduced dimensional distortion before cutting and measurement.

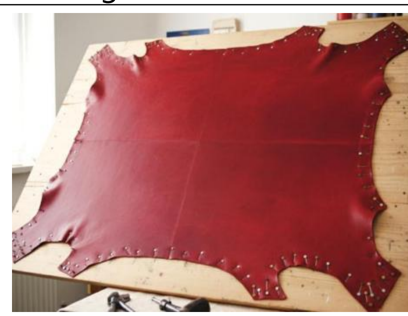
A 	B 
Sanding to remove excess flesh.	Soaking to soften the leather.
C 	D 
Soaping to eliminate odour.	Manual stretching and drying.

Figure 4A-D: Post-tanning preparation procedures used before characterization. Photograph by Victor Boateng-Nimoh, DIAT Leather Studio, May 2024

3.5 Anatomical Zoning

Each hide was divided into four anatomical zones: bend, shoulder, belly, and neck. (Refer to **Figure 5).** Zoning followed (Food and Agriculture Organization, 2010) guidance on hide and skin improvement. From each zone, square samples measuring 10 × 10 cm and tensile-strip

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samples measuring 15 × 2 cm were extracted. Samples were flattened mechanically and sealed in moisture-resistant bags to maintain stability before testing. (Refer to **Figure 6 A&B)**

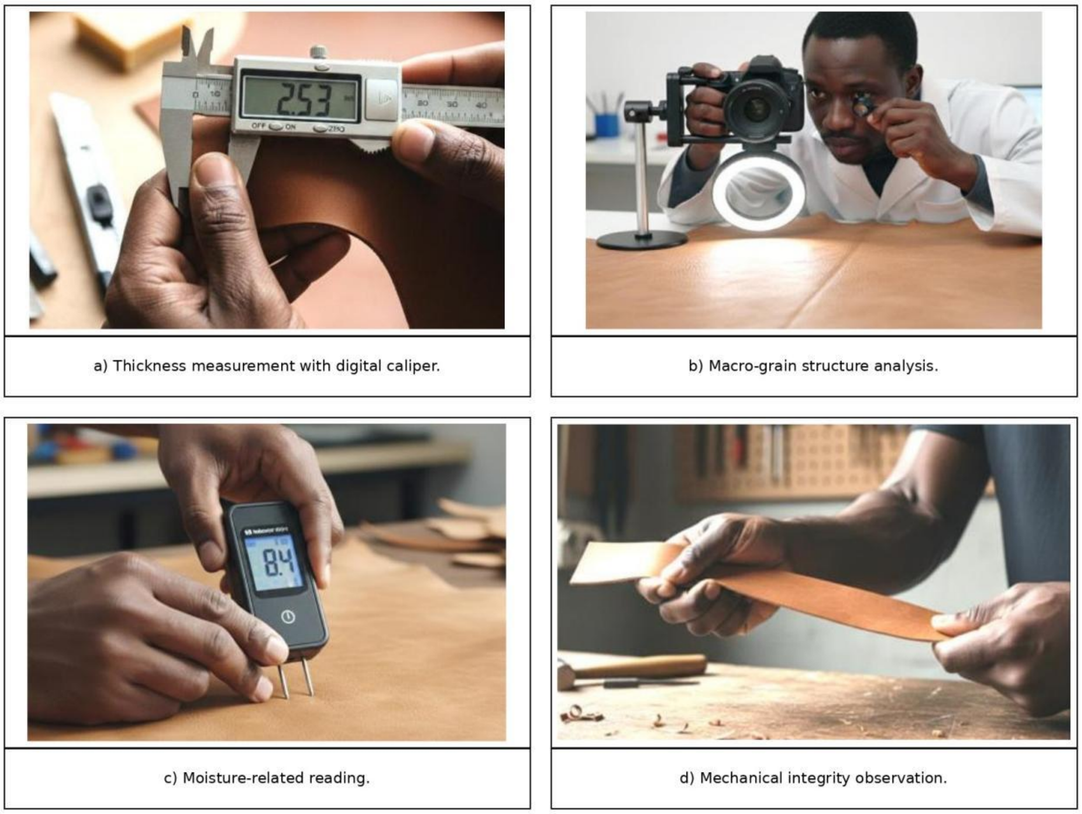
Figure 5: Anatomical zones of GIVTL. Source: Adapted from FAO (2010).

A 	B 
A) 10 × 10 cm leather samples.	B) Flattening and mechanical conditioning.

Figure 6A&B: Leather samples flattened and mechanically conditioned. Photograph by Victor Boateng-Nimoh, Researcher's Personal Studio, May 2024

3.6 Measurement Instruments and Procedures

The study adapted ISO/ASTM-aligned procedures suitable for resource-limited laboratory and studio settings. Thickness (**Figure 7A)** was measured using a digital caliper with ±0.01 mm precision, and five readings per sample were averaged. Macro-grain structure (**Figure 7B)** was examined using a 12-megapixel digital imaging system with 40× magnification and uniform LED illumination. Moisture content was determined using a Protimeter Mini pin-type digital moisture meter (Protimeter Ltd., Marlow, Buckinghamshire, United Kingdom). The meter was used to verify that the moisture content of each leather specimen was within the predetermined range before laser processing. (**Figure 7C)**. Mechanical integrity (**Figure 7D)** was evaluated using an adapted tensile-strip method derived from ASTM D2209, with samples scored on a 1-5 scale based on tear resistance and deformation behaviour.



a) Thickness measurement with digital caliper.

b) Macro-grain structure analysis.

c) Moisture-related reading.

d) Mechanical integrity observation.

Figure 7A, B, C & D: Measurement procedures used for thickness, moisture content, and macro-grain analysis. Photograph by Victor Boateng-Nimoh, Researcher's Studio, June 2024; moisture formula adapted from ISO 4684.

Conclusion

The methodology established a clear and systematic process for examining Ghanaian Indigenous Vegetable-Tanned Leathers. Through careful sampling, preparation, anatomical zoning, measurement, and data analysis, the study generated reliable evidence on how the bend, shoulder, belly, and neck zones differ in structure and laser-processing suitability. This approach ensured that the findings were both scientifically grounded and relevant to real Ghanaian leather-production and instructional contexts.

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3.7 Validity, Reliability, Ethical Considerations, and Data Analysis

Validity was strengthened through triangulated measurements of physical, mechanical, and morphological properties. Quantitative readings were taken three times and averaged, while inter-rater agreement for mechanical scoring exceeded 85%. No animals were harmed for this research; all 30 leathers were purchased ethically from ongoing artisanal operations. Photographs and observational documentation were taken with consent from tannery operators. Quantitative data were analysed using descriptive statistics, while qualitative grain-pattern data were interpreted thematically. Findings were interpreted employing Laser-Material Interaction Theory, Structure-Property Relationship Theory, and Materials Processing and Characterization Literature (Refer to Figure 9).

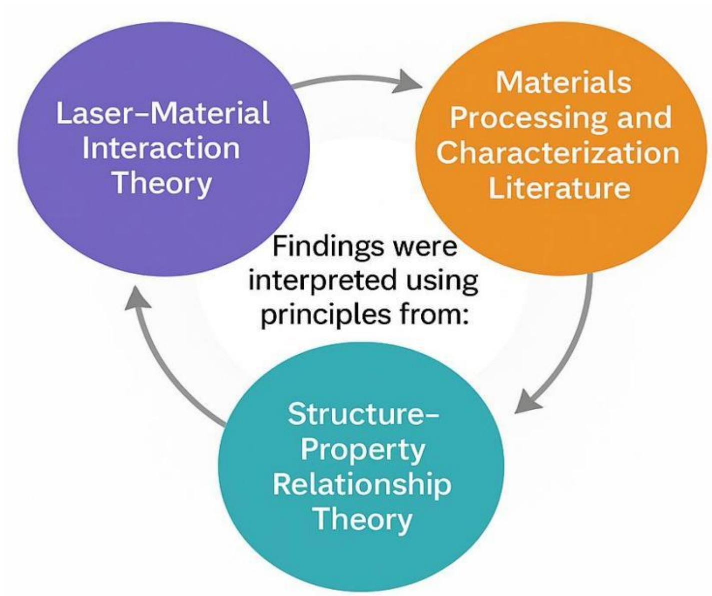

Figure 8: Interpretative Framework for Analysing GIVTL Material Behaviour. Source: Adapted from Shakil et al. (2023) and Callister and Rethwisch (2020).

Figure 9 illustrates the interpretative framework used to analyse the material behaviour of Ghanaian Indigenous Vegetable-Tanned Leathers (GIVTLs). It shows how laser–material interaction theory, structure–property relationship theory, and materials processing and characterization literature were combined to explain how zone-specific leather properties influence heat absorption, engraving clarity, cutting response, thermal stability, and overall suitability for laser processing.

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4. Results and Discussion

4.0 Overview

The results are organised around the four measured parameters: thickness, moisture content, grain morphology, and mechanical integrity. The section then integrates the findings to determine the relative laser-processing suitability of each anatomical zone.

4.1 Thickness Distribution and Dimensional Stability

This section presents the thickness variations across GIVTL anatomical zones and explains how dimensional stability affects laser engraving and cutting quality.

Table 1: Thickness distribution and dimensional stability of anatomical zones.

Anatomical Zone	Thickness (mm)	SD (mm)	Stability Rating	Remarks
Bend	2.1	± 0.2	High	Thickest and most uniform; best dimensional stability.
Shoulder	1.8	± 0.3	Moderate-High	Generally stable with minor variability.
Belly	1.3	± 0.4	Low	Thin and highly variable; structurally unstable.
Neck	1.4	± 0.5	Low	Irregular thickness; least consistent zone.

The results of data as presented in table 1 indicates that, thickness varied across the four anatomical zones. The bend exhibited the greatest dimensional stability, followed by the shoulder, which showed moderate uniformity. In contrast, the belly and neck zones presented pronounced irregularity, with fluctuations exceeding ±0.4 mm across most samples. These findings align with earlier studies showing that the bend region contains denser collagen bundles and fewer natural wrinkles, making it structurally stronger and more uniform (Gulbinienė et al., 2022; Sharmin et al., 2021).

For laser processing, consistent thickness is crucial because variability affects focal depth, heat distribution, and ablation stability (Steen & Mazumder, 2010). The stability of the bend zone therefore predicts cleaner engravings and more consistent cutting behaviour, while the irregular profile of the belly and neck may contribute to inconsistent engraving depth, incomplete cutting, and premature carbonization.

4.2 Moisture Content and Thermal Response

This section examines moisture levels across GIVTL anatomical zones and explains how moisture affects heat absorption, carbonization, and laser-processing stability as presented in table 2.

Table 2: Moisture content and thermal behaviour.

Anatomical Zone	Moisture Content (%)	Thermal Behaviour	Remarks
Bend	8.4	Stable	Lowest moisture; ideal for engraving.
Shoulder	9.1	Moderately stable	Acceptable thermal response.
Belly	10.7	Unstable	Higher moisture; carbonization risk.
Neck	10.9	Highly unstable	Prone to overheating and irregular engraving.

Moisture content followed a similar anatomical pattern. The bend recorded the lowest mean moisture value, while the belly and neck regions showed values above 10%. Higher moisture content can increase thermal diffusion and reduce engraving contrast by dissipating heat

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unevenly and contributing to shallow marks, localized charring, and inconsistent kerf formation (Li & Chen, 2018).

The bend and shoulder zones are therefore, more likely to produce cleaner engravings, sharper kerf edges, and reduced smoke. Moisture-rich belly and neck zones however, require conservative power, faster speeds, and test passes before production use.

4.3 Grain Structure and Fibre Arrangement

This section describes the grain compactness and fibre arrangement of GIVTL anatomical zones and explains how surface structure influences engraving clarity, heat flow, and cutting quality (Refer to table 3)

Table 3: Macro-grain structure across anatomical zones.

Anatomical Zone	Grain Structure	Observations
Bend	Compact, uniform	Minimal pores; consistent wrinkle pattern; stable surface.
Shoulder	Moderately compact	Acceptable grain cohesion.
Belly	Porous, irregular	Loose follicles; uneven texture; inconsistent surface.
Neck	Highly irregular	Deep wrinkles; scattered pores; weak grain alignment.

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Figure 10: Comparative macro-grain appearance of bend, shoulder, belly and neck zones. Photograph by Victor Boateng-Nimoh, Researcher's Studio, June 2024

The macro-grain observations (refer to figure 10) support previous anatomical analyses which note that grain compactness declines toward the belly and neck regions because of natural stretching, movement, and reduced collagen density (Mihai et al., 2022; Covington, 2011). Compact grains yield sharp, high-contrast markings, whereas porous surfaces scatter energy and produce coarse or fuzzy textures. This explains why belly and neck engravings often appear uneven or darker than those made on the bend.

Surface morphology is therefore, central to laser-material interaction. Compact, well-aligned grain conducts heat predictably and supports clean lines, consistent kerf widths, and minimal carbonization. Porous or wrinkled surfaces on the other hand, scatter energy, trap heat, and generate patchy engraving, burn halos, and rough edges.

4.4 Mechanical Integrity and Structural Cohesion

This section assesses the strength and cohesion of GIVTL anatomical zones and explains how mechanical stability affects cutting precision, edge quality, and resistance to deformation (refer to table 4).

Table 4: Mechanical integrity scores across anatomical zones.

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Anatomical Zone	Integrity Score (1-5)	Remarks
Bend	5	Strongest and highly cohesive; best resistance to tearing.
Shoulder	4	Good structural strength; moderate stability.
Belly	2	Weak; deforms easily under tension.
Neck	1	Very weak; tears quickly; structurally unstable.

Mechanical cohesion followed the expected anatomical gradient. The bend recorded consistently high cohesion, the shoulder showed moderate cohesion, the belly demonstrated reduced fibre stability, and the neck was the weakest zone. The superior mechanical stability of the bend supports its use in high-precision cutting, where strong fibre networks reduce fraying and produce cleaner edges (Sharmin et al., 2021).

Weak cohesion in the belly and neck increases susceptibility to tearing, charring, and rough edges during laser cutting. These zones should therefore be reserved for trials, low-precision marking, or creative experiments rather than final high-value products.

4.5 Integrated Interpretation of Findings

This section brings together the key findings to show how GIVTL anatomical zones differ in structural quality, thermal stability, and overall suitability for laser engraving and cutting (refer to table 5).

Table 5: Integrated laser-processing suitability of anatomical zones.

Zone	Structural Quality	Thermal Stability	Laser Suitability	Recommended Use
Bend	High	High	Excellent	Final products; high-precision engraving and cutting.

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Shoulder	Moderate	Moderate	Good	Medium-precision applications with parameter tuning.
Belly	Low	Low	Poor	Parameter testing and low-detail experiments.
Neck	Very low	Very low	Unsuitable	Testing zones only; not recommended for production.

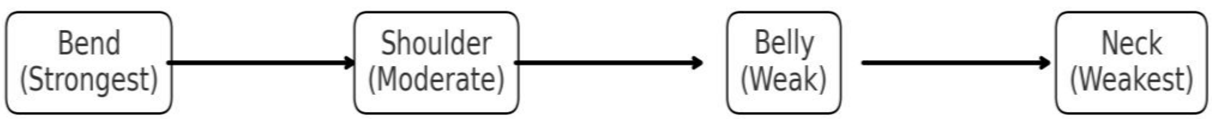

Figure 9: Anatomical hierarchy in structural performance. Source: Developed by the researcher (2025).

The findings reveal a clear anatomical hierarchy in structural performance. The bend consistently demonstrated superior dimensional stability, lower moisture content, compact grain, and strong mechanical cohesion. The shoulder showed moderate stability and is suitable for medium-precision work. The belly and neck exhibited higher moisture, irregular thickness, porous grain structures, and weaker fibre networks, explaining their poor engraving and cutting performance.

From the perspective of Laser-Material Interaction Theory, dense and low-moisture substrates dissipate heat more predictably and reduce uncontrolled carbonization. Porous and moisture-rich fibres absorb and distribute energy irregularly, causing uneven ablation, darkening, and thermal distortion (Steen & Mazumder, 2010). From the Structure-Property Relationship perspective, internal collagen architecture directly governs mechanical and thermal performance (Callister & Rethwisch, 2020). Thus, zone selection should be treated as a material-preparation decision rather than an afterthought in laser processing.

The result also demonstrates that adapted ISO/ASTM-informed procedures can be useful in low-resource contexts. Even when leather is produced through artisanal processes, its structural behaviour can be systematically characterized and interpreted. This makes it possible to develop practical and localized guidelines for GIVTL processing in Ghanaian art, design, and technology education settings.

5. Conclusion

This study revealed distinct anatomical and structural variations across the bend, shoulder, belly, and neck zones of Ghanaian Indigenous Vegetable-Tanned Leathers. The bend consistently demonstrated superior dimensional stability, lower moisture content, compact grain patterns, and stronger fibre cohesion, while the belly and neck showed greater irregularity including, higher moisture, and weaker mechanical integrity. These zone-specific differences confirm that collagen architecture strongly influences material performance and directly shapes how GIVTLs respond to diode-laser processing. The findings provide a scientific foundation for evidence-based parameter selection, material zoning, waste reduction, and instructional planning for laser engraving and cutting in Ghanaian leather-art education and production environments.

6. Recommendations

The findings of this study point to the need for more systematic, evidence-based approaches to the selection, preparation, and laser processing of Ghanaian Indigenous Vegetable-Tanned Leathers. Based on the observed differences in thickness, moisture content, grain structure, and mechanical integrity across the anatomical zones, the following recommendations are proposed to guide leather art education, studio practice, and future research.

1. Leather art educators should incorporate anatomical zoning and material-characterisation activities into practical lessons on laser engraving and cutting. Learners should be guided to identify the bend, shoulder, belly, and neck zones before selecting areas for production work.

2. Instructors and studio technicians should prioritise the bend zone for high-precision engraving and cutting, while using the shoulder for medium-precision work after test passes. The belly and neck should be treated cautiously and reserved mainly for trials, samples, and low-detail experimental tasks.

3. Training workshops should include simple pre-processing checks such as thickness measurement, moisture assessment, surface inspection, and test engraving. These checks can help students select appropriate power, speed, and pass settings before working on final artefacts.

4. Departments and leather studios should develop localized laser-processing charts for Ghanaian Indigenous Vegetable-Tanned Leathers based on anatomical zones and material condition. Such charts can serve as quick reference guides for students, artisans, instructors, and private laser operators.

4. Further studies should extend this anatomical characterization into controlled parameter-optimization experiments using different laser powers, speeds, passes, leather colours, and surface treatments. Future work should also validate the findings through the production and assessment of culturally reflective leather artefacts.

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Conflicts of Interest:
The authors declare no conflicts of interest.

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Author contribution

The contribution to the paper is as follows:
V. Boateng-Nimoh, K. Asubonteng: study conception, theoretical framework, and model development;
V. Boateng-Nimoh, H. B. Essel: literature synthesis, manuscript writing and editing;
All authors: critical review, final draft approval, and alignment of model with contextual data.

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