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Shrinkage Temperature of Vegetable-Tanned Cow, Goat and Sheep Hides and Skins Previously Exposed to Low-Dose Electron-Beam Irradiation

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ABSTRACT
Shrinkage temperature is a hydrothermal parameter used to assess the response of collagen-containing materials to heating in water. This study reports shrinkage-temperature measurements of cow, goat and sheep hides and skins following nominal low-dose electron-beam irradiation. Eighteen specimens were examined, comprising six pieces from each species. For each species, one specimen was assigned to each of six nominal dose levels: 0, 5, 10, 20, 30 and 50 Gy. Irradiation was performed before vegetable tanning, and each species-dose combination contained only one specimen. Recorded control shrinkage temperatures were 75.7 °C for cow, 74.7 °C for goat and 76.0 °C for sheep. Across the tested doses, cow values ranged from 69.6 °C at 5 Gy to 75.5 °C at 20 Gy; goat values ranged from 69.6 °C at 50 Gy to 74.8 °C at 5 Gy; and sheep values ranged from 73.7 °C at 10 Gy to 75.5 °C at 5 Gy. At 50 Gy, shrinkage-temperature readings were 72.4 °C for cow, 69.6 °C for goat and 74.0 °C for sheep, representing decreases of 3.3, 5.1 and 2.0 °C, respectively, relative to controls. Dose values represent nominal irradiation settings because independent absorbed-dose verification was not documented. Given the single specimen per species-dose combination, findings are descriptive and do not permit estimation of within-group variability or statistical inference. The observed differences alone do not establish radiation-induced changes in collagen stability. These measurements provide preliminary comparative data on shrinkage-temperature readings in tanned leather produced from hides and skins exposed to low nominal electron-beam doses.

Keywords: Shrinkage Temperature, Electron-Beam Irradiation, Linear Accelerator, Cow Hide, Goat Skin, Sheep Skin, Collagen, Hydrothermal Stability

INTRODUCTION

Animal hides and skins are important raw materials for leather manufacture. Their collagen-rich dermal structure is transformed through processing and tanning into materials with useful physical and mechanical properties. The thermal response of collagen depends on its source, molecular organisation, processing history and environmental conditions. Shrinkage-temperature measurement provides an indicator of the hydrothermal behaviour of hide-, skin- and leather-derived materials (Covington & Wise, 2020; Zhang et al., 2020). However, this parameter should be interpreted alongside other material characteristics rather than as a standalone measure of collagen cross-link density or finished-leather quality.

Microbial activity can cause deterioration of raw hides and skins when preservation and processing are delayed. Salting and drying are widely used to limit such deterioration, while alternative preservation and processing technologies continue to receive attention (Covington & Wise, 2020; Khambhaty & Samidurai, 2024). Ionising radiation has also been investigated for hide preservation. For example, Gaidau et al. (2021) examined gamma irradiation at kilogray-level doses, evaluating microbial load alongside material characteristics. Although relevant to radiation-based hide treatment, that study differs from the present work in both radiation modality and dose range. Specifically, 25 kGy is equivalent to 25,000 Gy, which is 500 times the upper nominal dose of 50 Gy used in this study. Consequently, findings on antimicrobial effectiveness at kilogray-level doses cannot be directly extrapolated to the low nominal doses examined here.

Previous studies have demonstrated that collagen responses to irradiation may depend on the material's physical state and treatment conditions. Apsimon et al. (2021) discussed accelerator design and particle-transport considerations relevant to electron-beam treatment, providing technical context for beam geometry and dose distribution. Dąbrowska-Gralak et al. (2022) investigated the influence of humidity on the response of type I collagen to electron-beam irradiation, while Šupová et al. (2023) examined differences in the responses of collagen in dry and gel states. These studies provide useful background but do not directly establish the shrinkage-temperature behaviour of vegetable-tanned leather produced from irradiated whole hides and skins. Other investigations have examined collagen thermal stability and the influence of environmental conditions and molecular composition (Fujii et al., 2022; Walker et al., 2021; Zhang et al., 2020). Similarly, reviews of collagen-based biomaterials describe approaches to matrix modification but do not establish the mechanisms responsible for the shrinkage-

temperature values observed in the present study (Huang et al., 2022).

Shrinkage temperature is an established parameter in leather testing and is addressed by ISO 3380:2015, which covers the determination of leather shrinkage temperature up to 100 °C. Alternative measurement approaches have also been reported (Esteban et al., 2021). In this study, the laboratory procedure was described with reference to SATRA TM17:1997, with the operational endpoint recorded as the temperature at which the leather strip shrank to one-third of its original length. Specifying the measurement procedure and endpoint is important for interpreting the recorded values and comparing them with results obtained using other procedures.

The present study forms part of a broader research programme investigating modifications in selected animal hides and skins following low-dose electron-beam irradiation using a medical linear accelerator. Related publications have reported bacterial-load measurements following irradiation (Akawu et al., 2026a) and variations in the thickness and apparent density of tanned leather produced from irradiated samples (Akawu et al., 2026b). Earlier work by Akawu et al. (2023) investigated gamma irradiation as an alternative to conventional salt curing for animal-hide preservation. Whereas these publications address microbial load, physical properties and preservation using different experimental approaches, the present study focuses specifically on shrinkage-temperature measurements in vegetable-tanned cow, goat and sheep hides and skins previously exposed to nominal electron-beam doses. Its contribution is therefore the descriptive comparison of this additional leather property within the broader research programme. The related publications are outputs from the same programme and should not be interpreted as independent replications; any overlap in specimens or experimental records should be understood in relation to the specific measurements reported in each publication.

The nominal dose range of 5–50 Gy was used within the constraints of the available medical linear-accelerator facility and the broader research programme investigating low-dose electron-beam exposure. The selected range provides a basis for describing and comparing recorded shrinkage-temperature values across increasing nominal exposure levels, although the doses were not independently verified as absorbed doses. Research specifically documenting the shrinkage-temperature behaviour of vegetable-tanned hides and skins previously exposed to this low nominal electron-beam dose range remains limited in the literature considered here.

This study therefore aims to evaluate and compare the recorded shrinkage-temperature characteristics of vegetable-tanned cow, goat and sheep hides and skins previously exposed to nominal electron-beam irradiation doses of 0–50 Gy. This aim accurately reflects the descriptive nature of the study without implying that causal dose effects can be established.

MATERIALS AND METHODS

Study Design, Sample Provenance and Allocation

Raw cow hides, goat skins and sheep skins were used in this study. Six pieces were obtained from each species, giving a total of 18 specimens and each sample cut in identical sizes of 10x10 cm^2. For each species, one piece was assigned to the unirradiated control group (0 Gy), while the remaining five pieces were individually assigned to nominal electron-beam irradiation doses of 5, 10, 20, 30 and 50 Gy. Thus, each species-dose combination was represented by a single specimen, with six specimens per species. The individual hide or skin piece constituted the experimental unit. Following irradiation, the specimens were processed by vegetable tanning. Accordingly, the shrinkage-temperature measurements reported in this study were obtained from tanned leather produced from hides and skins irradiated before tanning.

The raw hides and skins were obtained following slaughter and prepared for irradiation. The materials were collected within two hours after flaying. The specimens were washed with clean water, prepared into pieces measuring approximately 10 cm × 10 cm, placed in sterile polyethylene bags and kept cool in a container at a temperature of 4^0 C before irradiation in order to keep them from microbial attack while conveying them to the location for irradiation. This took 5 hours in – between collection and preservation. The initial material consisted of raw, untanned hides and skins, and irradiation was performed before vegetable tanning.

The individual hide or skin piece was treated as the experimental unit for descriptive reporting. Because only one specimen was available for each species-dose combination, independent replication within groups was not achieved. The dataset therefore does not permit reliable estimation of biological variability or inferential comparison of species and irradiation doses. The findings are interpreted as descriptive observations from the specimens examined.

Electron-Beam Irradiation Procedure

Electron-beam irradiation of the selected animal hides and skins was carried out using an ELEKTA SYNERGY medical linear accelerator at National Hospital Abuja, Nigeria. The available equipment record specified a nominal electron energy of 6 MeV, a 10 cm × 10 cm applicator and a monitor-unit delivery-rate setting of 400 monitor units per minute (MU/min). The record also indicated a 6 MV photon setting; however, this photon setting was distinguished from the 6 MeV electron-beam mode used for the present study.

The specimens were assigned to five nominal irradiation-dose groups: 5, 10, 20, 30 and 50 Gy. Unirradiated specimens served as controls. The 10 cm × 10 cm applicator was used for the irradiation arrangement, and the specimens were subsequently processed through the prescribed beamhouse, tanning-yard and finishing operations. The resulting tanned leather specimens were evaluated for shrinkage temperature.

The absorbed dose, expressed in grays (Gy), represents energy deposited per unit mass, with 1 Gy equivalent to 1 joule per kilogram. However, the monitor-unit delivery rate alone does not establish the absorbed dose received by the specimens. Electron-beam output must be related to monitor units using appropriate calibration data and irradiation conditions. The International Atomic Energy Agency (IAEA, 2000) describes a reference-dosimetry framework for determining absorbed dose to water in external radiotherapy beams. Similarly, Pawiro et al. (2022) demonstrated the importance of calibrated dose-per-monitor-unit measurements for electron beams generated by ELEKTA Synergy and Versa HD linear accelerators.

For the present study, the assigned dose levels are therefore reported as nominal doses because independent absorbed-dose measurements at the specimen positions, dose-uniformity results and the applicable calibrated electron-beam output were not available for confirmation. Accordingly, the recorded monitor-unit delivery rate is reported as an equipment setting and is not treated as independent verification of the dose absorbed by the hides and skins.

Tanning Process

The stages and procedures for tanning were according to Covington, (1997). These stages include beam house operation, tanning yard operation and finishing yard operation.

Beamhouse Operation

The beam house operation includes the following stages:

Soaking: - The skin was pre-soaked in water at room temperature plus detergent for 2 hours to remove dirts and drained on beam.

Unhairing: - Water was added to the skin at room temperature, followed by sodium sulphide and pulped for 60 min to remove and loosen hair and epidermal cells.

Liming: - Calcium hydroxide was added to the pelt for 2 hours, followed by water to cover and then left for 24 hours.

Deliming: - The limed pelt was delimed in water and ammonium sulphate salt for 60 min and checked for deliming using phenolphthalein (pH 8 to 9).

Bating: -This was carried out with bate powder for 25 min, then drained and washed twice.

Pickling: -The pelt was acidified in water, a very small amount of Sodium chloride and formic acid respectively at room temperature, it was run for 20 min and then run for 1 hour after which it was left stationary overnight. pH was checked (4.0 to 5.5).

Tanning Yard Operation

This includes the following stages:

Tanning*:* -This was carried out using the same pickle liquor in short float tannage. For Dividivi tannage, each one of the pickled pelt was tanned with crushed Dividivi (Caesalpinia coriaria) at intervals of 30 min.

Fat liquoring: -This was carried out for both tannages in one part of leather plus 0.6 part of water at 50 ^{o}C with 0.04 part of fat liquor for 45 min, then 0.01 part of formic acid was added and run for another 15 min.

Finally, the tanned leather was drained, washed, tested for shrinkage temperature and hung to dry; furthermore, it was conditioned, staked, toggled, trimmed, buffed and de-dusted and then taken for physical and mechanical tests.

Shrinkage-Temperature Measurement

Shrinkage temperature is determined according to the principle described in SATRA TM17:1997, *Shrinkage Temperature of Leather*. The method involves gradually heating a wetted leather specimen in water and recording the temperature at which sudden, irreversible shrinkage occurs. For the SATRA procedure, leather specimens measuring approximately 80 mm × 10 mm are prepared in two orientations: along the backbone direction and perpendicular to it (across direction). Where the backbone direction cannot be established, the tighter direction of the leather is taken as the along direction. Holes are punched at the ends of each specimen to facilitate suspension in the test apparatus. Before testing, the specimens are immersed in deionised or demineralised water for at least five minutes.

The shrinkage-temperature apparatus consists of a transparent sight chamber connected to a water reservoir or boiler that provides a circulation circuit. The wetted leather specimen is suspended vertically in the chamber, with its upper end secured to a hook and a small weight attached to its lower end. An adjustable external marker is positioned to assist observation of movement during heating. A thermometer is placed alongside the specimen to monitor the temperature of the surrounding water.

After the apparatus has been closed, the water is heated gradually. SATRA's published description indicates a heating rate of approximately 4 °C/min for this apparatus. The specimen is observed continuously, and the temperature is recorded when rapid shrinkage becomes apparent, indicated by a sudden reduction in specimen length of at least several millimetres. The temperature is recorded to the nearest degree Celsius. The apparatus incorporates a safety valve that limits pressure to the level corresponding to approximately 120 °C.

Data Handling and Analysis

One shrinkage-temperature value was available for each species-dose combination. Data were summarised descriptively to compare the recorded values among cow, goat and sheep specimens across the six nominal dose levels, including the unirradiated controls. The absolute change in shrinkage temperature relative to the corresponding species-specific control was calculated using:

$$\Delta T = T_d - T_0, \quad (1)$$

Percentage change in shrinkage temperature:

$$\Delta T(\%) = \frac{T_d - T_0}{T_0} \times 100 \quad (2)$$

Where T_d is the shrinkage temperature at a specified nominal irradiation dose, and T_0 is the corresponding control shrinkage temperature.

The calculated changes were derived directly from the recorded shrinkage-temperature values and did not constitute additional measurements. Results were presented descriptively and rounded to one decimal place. Because only one specimen represented each species-dose combination, within-group variability could not be estimated, and standard deviations, confidence intervals and inferential statistical tests were not calculated. Accordingly, the comparisons are descriptive and are not interpreted as demonstrating statistically significant differences or causal dose effects

RESULTS AND DISCUSSION

Recorded Shrinkage Temperature Values

The recorded values for the three species are presented in Table 1. Control readings were 75.7 °C for cow, 74.7 °C for goat and 76.0 °C for sheep. The cow reading was 69.6 °C at 5 Gy, 71.6 °C at 10 Gy and 75.5 °C at 20 Gy, before decreasing to 73.3 °C at 30 Gy and 72.4 °C at 50 Gy. The goat reading was 74.8 °C at 5 Gy, followed by 73.5, 73.2, 71.9 and 69.6 °C at 10, 20, 30 and 50 Gy, respectively. Sheep readings were 75.5 °C at 5 Gy, 73.7 °C at 10 Gy, 75.4 °C at 20 Gy, 74.5 °C at 30 Gy and 74.0 °C at 50 Gy. The cow and sheep sequences were non-monotonic, whereas the goat readings were lower than the control at doses of 10 Gy and above.

Table 1: Recorded Shrinkage-Temperature Values for Cow, Goat and Sheep Samples at Each Nominal Dose

Nominal dose (Gy)	Cow (°C)	Goat (°C)	Sheep (°C)
0	75.7	74.7	76.0
5	69.6	74.8	75.5
10	71.6	73.5	73.7
20	75.5	73.2	75.4
30	73.3	71.9	74.5

Nominal dose (Gy)	Cow (°C)	Goat (°C)	Sheep (°C)
50	72.4	69.6	74.0

One piece was assigned to each species-dose combination; the table therefore contains individual recorded values rather than replicate means.

Differences relative to control values

Absolute and percentage differences calculated from Table 1 are shown in Table 2. At 5 Gy, the cow reading was 6.1 °C below its control, the goat reading was 0.1 °C above its control, and the sheep reading was 0.5 °C below its control. At 20 Gy, the cow reading was 0.2 °C below its control. At 50 Gy, readings were lower than controls by 3.3 °C for cow, 5.1 °C for goat and 2.0 °C for sheep. The 0.1 °C increase recorded for goat at 5 Gy is small and cannot be distinguished from measurement uncertainty because repeatability information is unavailable.

Table 2: Calculated Absolute and Percentage Differences Relative to The 0 Gy Control; Percentage Change

Dose (Gy)	Cow Δ (°C)	Cow Δ (%)	Goat Δ (°C)	Goat Δ (%)	Sheep Δ (°C)	Sheep Δ (%)
5	-6.1	-8.1	0.1	0.1	-0.5	-0.7
10	-4.1	-5.4	-1.2	-1.6	-2.3	-3.0
20	-0.2	-0.3	-1.5	-2.0	-0.6	-0.8
30	-2.4	-3.2	-2.8	-3.7	-1.5	-2.0
50	-3.3	-4.4	-5.1	-6.8	-2.0	-2.6

All values are calculations from Table 1, not additional experimental measurements.

Discussion

Interpretation of the Recorded Patterns

The recorded values show different descriptive patterns across the three species. The cow series falls from 75.7 °C in the control to 69.6 °C at 5 Gy, rises to 75.5 °C at 20 Gy, and then decreases at 30 and 50 Gy. The goat series shows a small increase at 5 Gy followed by progressively lower recorded values at higher doses. The sheep series fluctuates rather than declining steadily with nominal dose. Since only one piece was assigned to each species-dose combination, these differences cannot establish a dose response, a species effect or an interaction between species and dose. The increase in the cow reading between 5 and 20 Gy could not be described as recovery, stabilisation or evidence of an optimum dose. For emphasis, these are differences between individual specimens rather than statistically established treatment effects.

The cow and sheep values fluctuate across the dose levels, whereas the goat values decline from 5 Gy onwards. Therefore, these observations should not be interpreted as definitive species-specific radiation responses.

Differences in collagen source, moisture content, anatomical site, preservation history and tanning conditions may influence hydrothermal behaviour (Covington & Wise, 2020; Zhang et al., 2020). These are plausible sources of variation, not mechanisms demonstrated by this dataset. Studies of collagen helices have linked thermal stability with molecular composition and environmental temperature (Fujii et al., 2022; Walker et al., 2021), but those findings cannot be transferred directly to whole hides or tanned leather without matching the material state and conditioning conditions. Shrinkage temperature describes a response under a particular test procedure; it does not independently quantify collagen cross-link density, chain scission, oxidation or disruption of the collagen triple helix.

Relationship to Previous Irradiation Studies

Previous studies have investigated the effects of ionising radiation on animal hides, leather and collagen-based materials. However, meaningful comparison requires consideration of radiation modality, absorbed dose, material condition at irradiation, processing history and the properties measured. These factors are particularly important in the present study because cow, goat and sheep hides and skins were exposed to nominal electron-beam doses of 5–50 Gy before vegetable tanning, and shrinkage temperature was measured after subsequent leather processing.

Gaidau et al. (2021) investigated gamma irradiation of bovine hides and leather at doses of 25, 35 and 50 kGy. Their assessment included microbial load, shrinkage temperature, collagen-related characteristics and other material-quality parameters. The study provides relevant background on the relationship between irradiation and hide or leather properties. Nevertheless, the dose difference between their work and the present study is substantial. The lowest dose used by Gaidau et al. (25 kGy) is equivalent to 25,000 Gy, which is 500 times the highest nominal dose of 50 Gy used in the present study. In addition, gamma irradiation differs from electron-beam irradiation in radiation delivery characteristics. Therefore, the findings of Gaidau et al. should be regarded as contextual evidence rather than directly comparable evidence for explaining the shrinkage-temperature readings obtained in the present investigation. Their findings cannot establish the expected response of leather to the much lower nominal doses considered here.

Apsimon et al. (2021) examined the design considerations for electron-beam systems intended to modify collagen materials, including beam distribution, particle transport and the achievement of uniform dose distribution. Their work is relevant to understanding the technical requirements of electron-beam treatment of collagen-containing materials. However, it primarily addresses accelerator design and beam-transport considerations rather than validating shrinkage-temperature measurements from irradiated, vegetable-tanned leather. It therefore supports the importance of irradiation geometry and dose distribution but does not independently verify the absorbed doses or explain the particular temperature patterns observed in the present study.

Further insight into possible radiation-related changes in collagen is provided by Šupová et al. (2023), who investigated electron-beam irradiation of collagen in dry and gel states at doses of 1, 10 and 25 kGy. They reported that the response differed according to the physical state and water content of the collagen: irradiation of collagen gels was associated with increased cross-linking and changes in mechanical behaviour, whereas irradiation in the dry state was associated more strongly with collagen-chain scission and reduced stability in certain test environments. These findings demonstrate that the condition of collagen during irradiation can influence its subsequent response. However,

their experimental doses were in the kilogray range, substantially higher than the nominal 5–50 Gy range in the present study, and their collagen preparations were not equivalent to animal hides subsequently processed through vegetable tanning. Their findings consequently provide a basis for discussing the possible importance of moisture and material condition, but they do not establish the mechanism responsible for the observed shrinkage-temperature variations in the present specimens.

The differences between the present results and previous reports should therefore not be interpreted as evidence of contradictory findings. Rather, they reflect differences in experimental conditions and the limits of direct comparison. In the present study, the shrinkage-temperature readings varied non-monotonically across the dose series for cow and sheep, while the goat readings declined after a slight increase at 5 Gy. Such patterns may reflect differences in the original hides and skins, their condition before irradiation, subsequent tanning and finishing, or other sources of specimen-level variation. Because the study did not directly investigate collagen cross-linking, molecular degradation or structural changes, these explanations remain possible interpretations rather than demonstrated mechanisms.

The present study also forms part of a broader research programme investigating radiation-induced changes in selected animal hides and skins. Related publications from this programme have examined bacterial-load outcomes following electron-beam irradiation (Akawu et al., 2026a) and the thickness and apparent density of electron-beam-irradiated tanned leather (Akawu et al., 2026b). These studies provide complementary information about microbiological and physical characteristics associated with the research programme. However, they do not constitute independent replication of the shrinkage-temperature findings reported here, because they address different outcomes. Similarly, the earlier investigation by Akawu et al. (2023), which examined gamma irradiation as an alternative to conventional salt curing, provides background on the wider application of radiation in hide preservation but differs from the present work in radiation modality and research focus.

Taken together, the related literature establishes that radiation-related responses in collagen-containing materials depend on experimental conditions, including radiation type, dose and material state. Nevertheless, the available studies do not provide a direct basis for predicting the shrinkage-temperature response of cow, goat and sheep leather exposed to the nominal low-dose electron-beam range used here. The contribution of the present study is therefore its descriptive documentation of shrinkage-temperature readings in these three types of vegetable-tanned leather following the specified irradiation treatments, rather than proof of a general dose-response relationship or an optimum irradiation dose.

Scope and Limitations of the Study

The findings should be interpreted in light of several limitations. First, one specimen was used for each species–dose combination. Consequently, biological variability among hides and skins and the variability of the measurement procedure could not be estimated. The reported values are individual specimen readings rather than means derived from independent biological replicates. Inferential statistical tests and claims of statistically significant differences are therefore not justified by this dataset.

Second, although the available equipment record specified an ELEKTA SYNERGY medical linear accelerator, a nominal electron energy of 6 MeV, a 10 cm × 10 cm applicator and a monitor-unit delivery-rate setting of 400 MU/min, independently verified absorbed-dose measurements at the specimen positions and dose-uniformity information were not available. The assigned dose levels are consequently reported as nominal doses. This limitation restricts the extent to which the observed patterns can be attributed confidently to the exact absorbed dose received by each specimen.

Third, the specimens were irradiated before vegetable tanning. The measured shrinkage temperatures therefore reflect the combined history of irradiation, tanning, fatliquoring, drying, conditioning and finishing. Since the study did not separately characterise the collagen structure before and after each processing stage, the individual contributions of irradiation and subsequent leather processing cannot be distinguished.

Finally, the present investigation focused on shrinkage temperature. It did not include a storage trial, a microbial challenge associated with the specimens evaluated in this paper, or a complete assessment of tensile strength, elongation at break, tear strength, compression resistance and collagen structure. Consequently, the results cannot establish preservation efficacy, overall leather quality, an optimum irradiation dose or superior radiation tolerance of one animal species over another.

Future studies should include multiple independent hides or skins per species and dose, documented specimen provenance, traceable dosimetry, assessment of dose uniformity, controlled tanning and conditioning procedures, and replicated shrinkage-temperature measurements. Complementary microbiological, physicomechanical and structural analyses would provide a stronger basis for determining whether the observed patterns are reproducible and for assessing their practical significance for leather processing.

CONCLUSION

This study documented shrinkage-temperature readings for cow, goat and sheep hides and skins exposed before vegetable tanning to nominal electron-beam doses of 5, 10, 20, 30 and 50 Gy, together with unirradiated controls. At the nominal dose of 50 Gy, the recorded shrinkage temperatures were 3.3 °C lower for cow, 5.1 °C lower for goat and 2.0 °C lower for sheep than their respective control values. The readings varied non-monotonically across the dose series for cow and sheep, while the goat readings declined after a slight increase at 5 Gy.

The findings provide preliminary descriptive information on shrinkage temperature in vegetable-tanned leather produced from irradiated animal hides and skins. However, the use of one specimen per species–dose combination, the absence of independently verified absorbed-dose measurements and the potential influence of tanning and finishing limit the conclusions that can be drawn. Comparisons with previous gamma- and electron-beam irradiation studies must also account for differences in radiation modality, dose range and material condition. The present findings do not establish a causal radiation effect, a statistically supported dose-response relationship, an optimum dose or preservation efficacy. Further research incorporating independent replication, verified dosimetry and complementary material characterisation is required before stronger conclusions can be made about the effects of low-dose electron-beam irradiation on leather properties.

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