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EFFECTS OF GINGER AND ACETIC ACID MARINADES ON PH, COLOUR, COOKING LOSS AND MICROSTRUCTURE OF CAMEL *BICEPS FEMORIS* MUSCLE

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ABSTRACT

Camel meat remains underutilised due to its inherent toughness. While marinades containing plant extracts and organic acids are used empirically, the specific effects of acetic acid alone or combined with ginger extract on camel meat quality traits remain underexplored. Furthermore, previous studies have relied primarily on physicochemical assessments without systematic histological validation. This study characterised the individual and combined effects of ginger extract (9%) and acetic acid (1%) on some physicochemical and histological properties of camel biceps femoris after 48 h marination at 4°C. Acetic acid alone markedly decreased pH (4.83), whereas ginger extract showed moderate acidification (5.40), with the combination exhibiting an intermediate value (5.15) ($p < 0.05$, Kendall's $W = 0.678$). Cooking loss was highest in ginger-treated samples (47.05%) ($p < 0.05$, Kendall's $W = 0.395$), while acetic acid-treated samples (36.00%) and the combination's samples (37.94%) remained comparable to controls (33.25–35.53%) ($p > 0.05$). All marinades significantly increased brightness (L^*) (Kendall's $W = 0.790$), but redness (a*) was preserved only in ginger-containing treatments ($p > 0.05$). Yellowness (b^*) increased exclusively with ginger ($p < 0.05$, $W = 0.714$). Histological measurements showed no significant differences in fibre diameter (Kendall's $W = 0.029$) or extracellular space (Kendall's $W = 0.114$) (all $p > 0.05$), despite qualitative evidence of structural modifications, notably muscle and collagen fibres disintegration. These effects are especially apparent in the ginger-marinated group, while mix marinades group displayed intermediate modifications, with less pronounced fragmentation. The ginger–acetic acid combination emerged as the most balanced formulation, achieving moderate acidification, preserved water-holding capacity, and stabilised colour. These findings establish a mechanistic basis for optimising camel meat quality and support sustainable protein diversification. Future research should validate sensory outcomes for industrial adoption.

Key words: Acetic acid, *Biceps femoris*, camel, ginger, histology, meat quality

Global population growth continues to widen the gap between meat supply and demand, driving the need to enhance the palatability of underutilised sources such as meat from aged animals and tough cuts (Moon, 2018). Camel meat represents a promising solution to this deficit (Boukrouh *et al,* 2025), offering superior nutritional value, including high levels of polyunsaturated fatty acids, low cholesterol, a balanced profile of amino acids with high essential amino-acid index and B vitamins (Bougherara *et al,* 2023; Kadim *et al,* 2018; Raiymbek *et al,* 2015). However, camel meat, typically sourced from older animals, suffers from excessive toughness that limits consumer acceptability and industrial application (Djenane and Aider, 2024; Moeini *et al,* 2024).

Traditional marination with organic acids; including citric acid (He *et al,* 2015; Abd Elgadir *et al,* 2025), lactic acid (Aktaş *et al,* 2003; Chang *et al,* 2010), and acetic acid (Goli *et al,* 2014), as well as fermented products (Latoch *et al,* 2023) has proven effective for meat tenderisation. Notably, acetic acid offers additional antimicrobial properties (Chai and Sheen, 2021). Complementing acidic approaches, plant-derived proteases, particularly ginger cysteine proteases, have emerged as natural, cost-effective tenderisers (An and Kim, 2024), demonstrating

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efficacy across various meat types (Naveena and Mendiratta, 2004; Kumar *et al,* 2017; Erdem and Gökmen, 2025) including camel (Hoda and Ali, 2014; Jafari *et al,* 2020). While enzymatic treatments have been studied independently, both acetic acid alone and their combined effects on camel meat remain poorly characterised. Furthermore, most previous works have relied solely on physicochemical assessments without systematic histological validation. This study addresses these gaps by integrating histological and some physicochemical analyses to evaluate how ginger and acetic acid marinades, alone and in combination, affect camel thigh muscle structure and quality. Given that meat tenderness depends on myofibrillar protein integrity, connective tissue organisation, and intramuscular lipid content (Roy and Bruce, 2024; Kim *et al,* 2025; Xie and Grossmann, 2025), histological techniques provide precise quantification of structural changes induced by tenderisation treatments (Ghisleni *et al,* 2010; Sereda and Tatarnikova, 2019). By systematically mapping the relationship between marinade formulations and muscle microstructure, this research establishes a scientific foundation for optimising camel meat quality and expanding its potential for high-value industrial applications.

Materials and Methods

Ethical Statement: This study did not involve live animal experimentation or sacrifice for research purposes. Camel meat samples were obtained from commercially slaughtered dromedaries at local butcheries, where animals were processed according to standard commercial and Islamic halal slaughter practices.

Ginger extract preparation

Fresh rhizomes of *Zingiber officinale roscoe* were purchased from the central market of Batna, Algeria. Rhizomes were washed, peeled and finely sliced before homogenisation with an equal volume (1:1, w/v) of distilled water at 4°C for 2 minutes. The crude ginger extract (GE) was obtained by filtering the suspension through sterile muslin cloth.

Marinade solutions

Four marinade solutions were prepared fresh on the day of treatment: distilled water (C48+), 9% GE (v/v) as described by Naveena and Mendiratta (2004), 1% (v/v) acetic acid (AA), and a mixture of 9% GE + 1% AA (AG). Two controls without additives were included: one analysed immediately (C-) and another after 48 hours (C48-).

Meat samples and experimental design

Eighteen samples of *biceps femoris* muscle were taken from male dromedaries aged 3–7 years and collected 24–48 hours post-slaughter from the same local butchers throughout the study. These samples were transported to the laboratory using ice packs in an icebox under aseptic conditions. After carefully removing connective tissue and visible fat, portions from each animal were randomly assigned to the six treatment groups using a complete block design with the animal as the blocking factor. This repeated-measures design ensured that inter-animal variability was controlled. Excluding the C- and C48- control groups, all samples were uniformly sprayed with 15% marinade (15 mL/100 g meat, v/w) followed by manual massaging for 2 min to ensure even distribution. The pieces were then individually sealed in labelled storage bags and refrigerated at 4°C for 48 hours. C48- was stored under the same conditions without marinade application. After draining the exudates with absorbent paper, the raw samples were subjected to histological, pH, and colour analyses. The cooked samples were then assessed for their cooking loss. Sample preparation and physicochemical analyses were performed at the food science laboratory (LSA) of the Institute of Agricultural Sciences and Veterinary Sciences at the University of BATNA 1, Batna, Algeria, while histology was conducted at the histology-histopathology laboratory of the same institute.

Physicochemical analyses

pH ***measurements***. Five gm of samples were homogenised with 50 ml of distilled water (1:10) (w/v) (Dolores Romero De Ávila *et al,* 2014), and the pH of the homogenates was measured by a pH meter (Bante-210).

Cooking loss determination. Five gm of each sample was placed in a cooking bag and cooked for 75°C for 25min until the sample temperature reached 72°C (Choi *et al,* 2017). After cooking, the samples were slightly dried with paper towels and weighed 4 hours later. Cooking loss was determined by weighing samples before and after cooking, and calculated as follows:

$$\text{Cooking Loss (\%)} = [(W_{raw} - W_{cooked}) / W_{raw}] \times 100.$$

Where W_{raw} and W_{cooked} represent the sample weights before and after cooking, respectively

Colour evaluation. Each sample was assessed using the CIE *L*a*b** system, illuminant D65, and 10° for the standard observer, with a Chroma-meter

(Minolta) calibrated against a white standard, as stated by (Oliveira *et al,* 2021).

Histological analysis

For a more accurate assessment of the histological structure, three pieces from each sample were fixed for no less than 48h in buffered formalin (10%), dehydrated at increasing concentrations of ethanol, and then embedded in paraffin. The 5 µm sections were stained with hematoxylin-eosin (HE) to observe the muscle fibres and with Masson's trichrome (MT) to reveal the connective tissue. Both stains were performed according to the protocols mentioned in Manual of histological staining methods (1968). For quantitative and qualitative microstructural analysis, images were captured with a DMK33UX265 camera mounted on a LEICA DM 100 LED microscope and analysed using ImageJ 4.0 software to quantify fibre diameter and extracellular space, and to detect morphological changes in muscle components.

Statistical analysis

Statistical analysis was performed using IBM SPSS STATISTICS version 26. The dromedary was considered the experimental unit (n = 18); technical replicates were averaged prior to analysis. The effect of marinade treatment on meat quality parameters was evaluated using the Friedman test, with animal considered as the blocking factor. Effect size was quantified using Kendall's coefficient of concordance (W). When the Friedman test indicated significant differences ($p < 0.05$), pairwise comparisons were conducted using Wilcoxon signed-rank tests, with p-values adjusted for multiple testing using the Holm–Bonferroni method. Relationships between physicochemical and histological parameters were explored using Spearman's rank correlations (non-parametric, 21 pairwise variable combinations, k = 21). The results are presented as median (Q1-Q3).

Results and Discussion

Marinade treatments exerted a large effect on the pH values of camel meat (Kendall's W = 0.68, X^2= 61.02, $p < 0.001$). The highest pH was recorded in the fresh control group (C-: 5.88) (Table 1). After 48 h of storage, non-marinated (C48-: 5.52) and distilled-water-marinated controls (C48+: 5.37) exhibited a slight, non-significant decline ($p > 0.05$) reflecting mild post-mortem acidification. Ginger-marinated samples (GE: 5.40) showed comparable values to these controls. In contrast, marination with acetic acid (AA: 4.83) and the ginger–acetic acid combination (AG: 5.15) induced a pronounced pH drop, with AA exhibiting the lowest value among all treatments ($p < 0.05$).

The modest pH decrease observed in untreated samples aligns with the slow post-mortem glycolytic rate characteristic of camel muscle, which proceeds more gradually than in other red meats (Soltanizadeh *et al,* 2008). This natural acidification is primarily driven by residual lactic acid accumulation rather than proteolytic activity (Soltanizadeh *et al,* 2008). The absence of significant pH reduction in GE-treated samples suggests that the ginger extract, at the concentration applied, lacked sufficient acidifying potential to overcome the muscle's inherent buffering capacity. This finding contrasts with studies reporting significant pH decreases in ginger-marinated meat (Abdel-Naeem *et al,* 2022), y*et al*igns with others observing neutral effects attributed to the relatively high pH of ginger extracts themselves (Cruz *et al,*

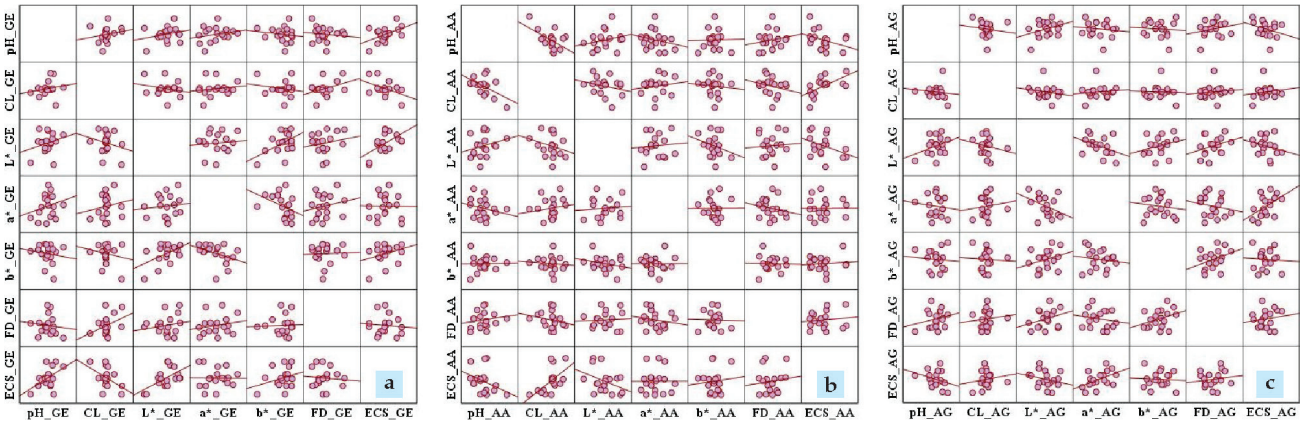

Fig 1. Matrix of pairwise Spearman correlations between pH, cooking loss, colour and histological parameters of camel meat treated with different marinades (n = 18 camels). **a.** GE group. **b.** AA group. **c.** AG group. Diagonal labels indicate variables: pH, CL (cooking loss), L^* (lightness), a^* (redness), b^* (yellowness), FD (fibre diameter), ECS (extracellular space).

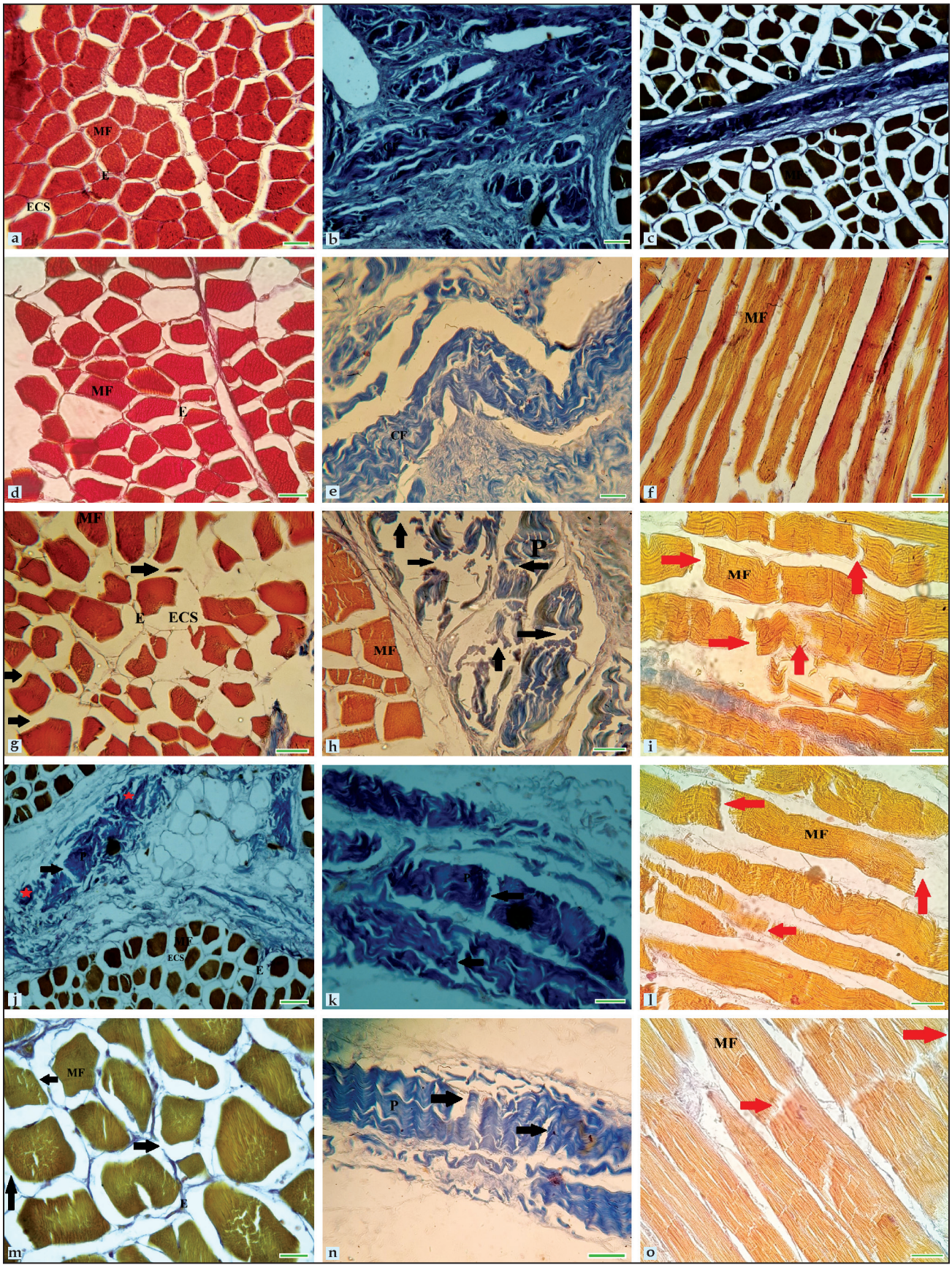

Fig 2. Effects of different marinades on muscle structure under the light microscope.

a: Cross-section of the control (C-) showing the typical organisation of muscle fibres (MF) with uniform diameter separated by minimal extracellular space (ECS), and well-preserved endomysium (E). Staining: H&E. Scale bar: 50 µm. **b:** Detailed view of the intact connective tissue architecture of C- with well-preserved collagen fibres (CF) and endomysium (E) surrounding the muscle bundles. Staining: Masson's trichrome. Scale bar: 50 µm. **c:** Cross-section of C48- revealing preservation of muscle architecture (MF) and Perimysium (P) with a slight increase in extracellular space compared to C-. Staining: Masson's trichrome. Bar: 50 µm. **d:** Cross-section of C48+ showing preserved muscle fibre organisation (MF) and relatively reduced extracellular space (ECS). H&E staining. Scale bar: 50 µm. **e:** Cross-section of C48+ revealing the integrity of connective structures (CF). Staining: Masson's trichrome. Scale: 50 µm. **f:** Longitudinal section of C48+ showing preserved muscle fibre organisation (MF). Staining; Masson's trichrome. Scale bar: 50 µm. **g:** Cross section of GE revealing fraying and cuts (black arrows) in the endomysium (E). Staining: Masson's trichrome. Scale bar: 50 µm. **h:** Cross-section of GE showing massive degradation (black arrows) of collagen fibres in the perimysium (P). Staining: Masson's trichrome. Bar: 40 µm. **i:** Longitudinal section of GE showing the disintegration (red arrows) of muscle fibres (MF). Staining: Masson's trichrome. Bar: 50 µm. **j:** Cross section of AA showing disorganisation (red asterisks) of collagen fibres in the perimysium (P). Staining: Masson's trichrome. Bar: 50 µm. **k:** Cross-section of AA showing collagen breakdown (black arrows) in the perimysium (P). Staining: Masson's trichrome. Bar: 30 µm. **l:** Longitudinal section of AA showing the disintegration (red arrows) of muscle fibres (MF). Staining: Masson's trichrome. Bar: 50 µm. **m:** Cross section of AG revealing fraying and cuts (black arrows) in the endomysium (E). Staining: Masson's trichrome. Bar: 30 µm. **n:** Cross-section of AG showing collagen breakdown (black arrows) in the perimysium (P). Staining: Masson's trichrome. Bar: 40 µm. **o:** Longitudinal section of AG showing the disintegration (red arrows) of muscle fibres (MF). Staining: Masson's trichrome. Bar: 50 µm.

Table 1. Impact of marinades on pH, cooking loss, and colour (*L**, *a**, *b**) of camel meat (*n=18*).

Parameter	Treatments						Effect		
	C-	C48-	C48+	GE	AA	AG	*W*	X^2	*p*
pH	5.88 (5.61 – 6.02)^{a}	5.52 (5.25 – 5.6)^{a}	5.37 (5.24 – 5.61)^{a}	5.40 (5.28 – 5.53)^{ac}	4.83 (4.60 – 4.91)^{bc}	5.15 (4.99 – 5.32)^{c}	0.68	61.02	<0.001
Cooking loss (%)	33.25 (31.95 – 35.18)^{a}	36.01 (34.59 – 37.99)^{a}	35.53 (33.39-39.45)^{a}	47.05 (44.90-50.05)^{b}	36 (28.53-37.88)^{a}	37.94 (31.43-41.09)^{a}	0.40	35.52	<0.001
Colour (*L, *a**, *b**)**									
*L**	38.30 (37.25 – 41.23)^{a}	39.20 (38.08 – 42.25)^{ab}	38.40 (37.33 – 39.98)^{b}	42.85 (41.75 – 43.95)^{c}	42.80 (41.28 – 44.33)^{c}	42.90 (41.50 – 43.88)^{c}	0.79	71.07	<0.001
*a**	16.30 (15.10 – 17.60)^{a}	15.90 (14.98– 17.18)^{a}	16.15 (15.43 – 17.28)^{a}	16.20 (14.25 – 17.95)^{a}	13.85 (11.68 – 15.98)^{b}	15.70 (14.88 – 16.60)^{ab}	0.32	28.59	<0.001
*b**	8.30 (7.38 – 9.10)^{a}	8.75 (7.43 – 9.33)^{a}	8.30 (8.20 – 8.85)^{a}	11.55 (10.55 – 12.18)^{b}	9.20 (8.68 – 9.73)^{a}	11.85 (10.55 – 12.70)^{b}	0.71	64.29	<0.001
Histological changements									
FD (µm)	51.49 (44.67 – 74.66)^{a}	42.19 (34.71 – 74.54)^{a}	53.09 (33.98 – 67.93)^{a}	47.59 (35.38 – 59.96)^{a}	54.14 (35.18 – 72.10)^{a}	56.13 (31.16 – 78.92)^{a}	0.03	2.64	0.76
ECS (%)	24.35 (19.95 – 28.81)^{a}	27.92 (19.91– 34.08)^{a}	25.26 (18.31 – 29.22)^{a}	30.24 (26.08 – 34.16)^{a}	25.8 (14.62 – 31.12)^{a}	23.99 (19.62 – 30.35)^{a}	0.11	10.22	0.07

Data presented as median (Q1–Q3). Different superscript letters (a, b, c) within rows indicate significant differences ($p < 0.05$) based on Wilcoxon signed-rank tests with Holm-Bonferroni correction. *W* = Kendall's coefficient of concordance (effect size). χ^2 = Friedman test statistic with *df* = 5 for all parameters.

C-: Fresh sample analysed immediately; C48-: Control after 48h refrigeration; C48+: Control with distilled water after 48h. GE: 9% ginger extract; AA: 1% acetic acid; AG: 9% ginger extract + 1% acetic acid. FD: Fibre diameter. ECS: Extracellular space.

2020). These discrepancies likely stem from variations in ginger concentration, extraction methods, and species-specific muscle properties.

The marked acidification in AA-treated samples directly results from the exogenous addition of protons from acetic acid (He *et al,* 2015), consistent with reports on organic acids (Unal *et al,* 2022; Abd Elgadir *et al,* 2025) and fruit juice marinades (Ünal *et al,* 2020).

Notably, the intermediate pH of the AG samples compared to AA samples indicates a partial buffering effect when ginger extract is mixed with acetic acid. This phenomenon may involve interactions between acetic and ginger bioactive compounds (such

gingerols, polysaccharides) (Yang *et al,* 2024) which modulate the net acidifying capacity and potentially protect muscle proteins from excessive denaturation (He *et al,* 2015).

Cooking loss

Marinade treatments exerted a medium-to-large effect on cooking loss (Kendall's $W = 0.40$, $X^2 = 35.52$, $p < 0.001$) (Table 1). Cooking loss ranged from 33.25% to 47.05% across treatments. The lowest value was observed in the fresh control group (C-: 33.25%), although it did not significantly differ from C48- (36.01%), C48+ (35.53%), AA (36%), or AG (37.94%) (all $p > 0.05$). Only GE-treated samples (47.05%) displayed significantly higher cooking loss compared to all other groups ($p < 0.05$), indicating a markedly reduced water-holding capacity during thermal processing.

The substantial increase in cooking loss observed with ginger marinade alone is likely related to extensive structural modifications that compromise the meat's ability to retain moisture during heating (Abdel-Naeem and Mohamed, 2016). This effect is essentially attributed to enzymatic proteolysis. Ginger's cysteine protease (zingibain) likely targets both myofibrillar proteins and connective tissue components, weakening the structural matrix and facilitating moisture release upon heating (Maqsood *et al,* 2018; Naqvi *et al,* 2021a; Vaskoska *et al,* 2021). The potential contribution of reduced fat retention, as suggested by Abdel-Naeem and Mohamed (2016) may further exacerbate this phenomenon. These findings align with reports on ginger treated beef (Naqvi *et al,* 2021b) and camel meat (Abdel-Naeem *et al,* 2022) where enzymatic tenderisation similarly increased cooking losses.

In contrast, the absence of significant cooking loss variation in AA and AG treatments, despite their marked acidifying effect, suggests that acid-induced protein denaturation alone was insufficient to substantially compromise water holding capacity under the applied conditions. This observation is consistent with (Cruz *et al,* 2020) who found that acidic marinade did not necessarily exacerbate cooking loss in chicken breast.

Notably, the intermediate cooking loss value in AG group compared to GE suggests that acetic acid may partially inhibit ginger's proteolytic activity, possibly through pH-dependent enzyme modulation (He *et al,* 2015) or interactions between bioactive compounds. Divergent observations in the literature, including improved cooking yield with ginger (Hoda and Ali, 2014) or increased losses of beef with citric acid (Klinhom *et al,* 2015), underscore the influence of intrinsic meat characteristics (species, age, fat distribution) and processing conditions (aging time, cooking parameters, marinade composition) on treatment outcomes (Tian *et al,* 2013; Sukada *et al,* 2019). These variations highlight the importance of optimising marinade formulations according to species-specific muscle properties.

Colour evaluation

Significant differences in colour parameters were observed among treatments (Table 1).

***Lightness* (*L**)**. Marinade treatments exerted large effects on L^* of camel meat (Kendall's $W = 0.79$, $X^2 = 71.07$, $p < 0.001$). Lightness (L^*) ranged from 38.30 to 42.90 across groups. Control samples (C : 38.30) showed no significant variation after 48 h storage, whether non marinated (C48 : 39.20) or distilled water marinated (C48+: 38.40) ($p > 0.05$). In contrast, all marinated samples (GE, AA, AG) ranging from 42.80 to 42.90 exhibited significantly higher L^* values compared to controls ($p < 0.05$), indicating a marked brightening effect. No significant differences in L^* were detected among the three marinated groups ($p > 0.05$). In ginger-marinated samples (GE), a positive correlation was observed between lightness (L^*) and extracellular space (ECS) ($\rho = 0.51$, $p = 0.031$) (Fig 1a). No other significant correlations were detected among the 21 pairwise comparisons tested in the GE group (all $p > 0.05$).

***Redness* (*a**).** Redness (a^*) varied between 13.85 and 16.30 (Kendall's $W = 0.32$, $X^2 = 25.59$, $p < 0.001$), indicating a medium effect of treatments on this parameter. Controls (C, C48, C48+) displayed comparable values (15.90 - 16.30; $p > 0.05$). Among marinated samples, GE (16.20) and AG (15.70) maintained redness similar to controls ($p > 0.05$), whereas AA (13.85) showed significantly lower redness than all other groups ($p < 0.05$) except AG ($p > 0.05$).

***Yellowness* (*b**)**. Yellowness (b^*) ranged from 8.30 to 11.85 (Kendall's $W = 0.71$, $X^2 = 64.29$, $p < 0.001$), representing a large treatment effect. Control groups displayed similar values (8.30–8.75; $p > 0.05$). GE (11.55) and AG (11.85) showed significantly higher b^* than all controls and AA (9.20) ($p < 0.05$). AA did not differ from controls ($p > 0.05$), while AG yielded the highest yellowness among all treatments.

The systematic brightening indicates a common effect of marination on the optical properties of camel muscle, independent of marinade composition,

although the underlying mechanisms may differ. The underlying mechanism may probably involve protein denaturation (Jankowiak *et al,* 2021), which alters light scattering properties of myofibrillar structures and promotes surface moisture accumulation, both enhancing reflectance (Hughes *et al,* 2020; Purslow *et al,* 2020). Similar brightening effects have been reported in poultry marinated with citric acid (Unal *et al,* 2022), ginger-treated goat meat (Putra *et al,* 2019) and camel meat burgers (Abdel-Naeem and Mohamed, 2016), confirming that both acidification and enzymatic treatments influence meat lightness. Notably, in ginger-marinated samples (GE), the positive correlation observed between *L** and extracellular space confirms that structural modifications induced by ginger proteolysis, which enlarge intercellular gaps, concurrently enhance light scattering properties, resulting in a brighter appearance independently of direct pH effects. This finding aligns with previous reports showing that myofibrillar degradation increases light reflectance in marinated meats (Hosseini and Esfahani Mehr, 2015; Gagaoua *et al,* 2020). The absence of this correlation in AG marinade further supports the hypothesis that acetic acid moderates enzymatic activity, preserving structural integrity and limiting excessive light scattering relative to GE and decoupling light scattering from excessive proteolysis.

The marked reduction observed in redness (*a**), with acetic acid alone, indicates accelerated myoglobin oxidation, converting cherry red ferrous oxymyoglobin (Fe^{2+}) to brown ferric metmyoglobin (Fe^{3+}), which leads to meat browning (Gagaoua *et al,* 2020; Hughes *et al,* 2020). This pro oxidant effect is characteristic of acidic environments, where oxymyoglobin destabilisation releases free iron that generates pro-oxidant radicals, catalysing pigment oxidation (Ke *et al,* 2009). However, the stability of redness in samples containing ginger (GE and AG) demonstrates the antioxidant capacity of ginger polyphenols (Yang *et al,* 2024). These compounds neutralise free radicals and reactive oxygen species, limiting lipid peroxidation and protecting myoglobin from oxidation (Mancini *et al,* 2017; Ivane *et al,* 2022). The preservation of redness in AG despite the presence of acetic acid, indicates that ginger's antioxidant activity effectively counteracts the pro oxidant effect of acidification, a finding with direct implications for consumer acceptability, as redness is a primary visual cue for meat freshness. This protection contributes to preserving red meat colour, thus improving its overall acceptability (Mancini and Hunt, 2005).

The significant increase in the yellowness index (*b**) in samples containing ginger (GE and AG) is directly attributable to the deposition or extraction of coloured phenolic compounds from the rhizome, particularly curcuminoids and related pigments (Mancini *et al,* 2017; Unal *et al,* 2022). The absence of *b** elevation with acetic acid alone confirms that this yellowing is not pH dependent but rather reflects direct pigment transfer from the marinade. These findings corroborate previous work on ginger marinated camel meat burgers (Abdel-Naeem and Mohamed, 2016) and goat meat (Putra *et al,* 2019).

Histological changes

Quantitative measurements. Marinade treatments exhibited negligible to small effects on the histological parameters of camel meat. Neither fibre diameter (Kendall's $W = 0.03$, $X^2 = 2.64$) nor extracellular space (ECS) (Kendall's $W = 0.11$, $X^2 = 10.22$) differed significantly among groups (all $p > 0.05$; Table 1). Although GE samples displayed a numerically higher median ECS (30.24%) compared to controls (24.35–27.92%) and other marinades (23.99–25.80%), the small effect size indicates that treatments explained only 11.4% of the variance in ECS. This suggests that quantitative fiber-level changes were limited, despite evidence of molecular-level modifications. Detailed median values for all groups are presented in table 1.

Correlation analysis. For acetic acid-treated samples (AA), cooking loss (CL) was positively correlated with extracellular space ($\rho = 0.57$, $p = 0.014$) (Fig 1b). This moderate correlation supports a mechanistic link between acid-induced structural reorganisation and variation in water retention within the group. Despite pronounced pH reduction in AA samples, pH itself did not correlate significantly with any other parameter (all $p > 0.05$), suggesting that acidification effects are mediated through intermediate mechanisms.

Notably, no significant correlations were detected in the combination treatment (AG) (all $p > 0.05$ for 21 pairwise comparisons) ((Fig 1.c)). This absence of correlations, contrasting with GE (*L**-ECS) and AA (C*L**ECS), suggests that combining ginger with acetic acid modulates their respective effects, possibly through pH-dependent enzyme inhibition or buffering interactions.

Qualitative microscopic examination. Qualitative microscopic examination revealed a treatment-specific pattern of structural modification that complements the quantitative measurements. Control samples (C-, C48-, C48+) exhibited well

preserved muscle architecture, characterised by intact, tightly bound muscle fibres surrounded by a regularly organised connective tissue matrix with uniform collagen distribution around bundles (Fig 2. a-f). This structural integrity confirms the absence of significant exogenous degradation and provides a valid baseline for assessing marinade induced modifications.

Ginger treated samples (GE) displayed visual evidence of connective tissue and myofibrillar protein alterations, including fragmentation of collagen fibres, reduced sarcolemma and apparent gaps between fibres (Fig 2. g-i). Although, these changes did not translate into statistically significant differences in fibre diameter or ECS measurements, they are consistent with zingibain activity, a cysteine protease that preferentially hydrolyses collagen and myofibrillar proteins (Kim *et al,* 2013; Kumar *et al,* 2017; Naqvi *et al,* 2021b). The resulting structural disruption may facilitate the expulsion of intracellular water into the extracellular matrix (Kahraman *et al,* 2012; Sharedeh *et al,* 2015), which can probably explain the elevated cooking loss observed in this group despite unchanged quantitative histology. Similar ginger induced structural changes have been documented across species (Abdel-Naeem and Mohamed, 2016; Abdel-Naeem *et al,* 2022; An and Kim, 2024), confirming the conserved proteolytic action of zingibain.

Acetic acid treated samples (AA) exhibited a different pattern, characterised by fibre fragmentation and slight expansion of intercellular spaces, accompanied by disorganisation of collagen fibres (Fig 2 j-l). These changes are primarily attributable to acid activated cathepsins, lysosomal enzymes with optimal activity in the pH range 3.5–5.0, that degrade both myofibrillar and connective tissue proteins (Mazaheri Kalahrodi *et al,* 2021; Latoch *et al,* 2023). The positive correlation between cooking loss and ECS observed specifically in this group provides direct mechanistic support for the link between acid induced structural loosening and impaired water retention, a relationship absent in controls where structure remained intact. Similar acid mediated degradation has been reported with various organic acids (Dilek *et al,* 2023; Zheng *et al,* 2024), underscoring the direct impact of pH reduction on muscle ultrastructure.

The combination treatment (AG) displayed intermediate modifications, with less pronounced fragmentation than GE alone but more evident changes than controls (Fig 2 m-o). This attenuated effect likely reflects pH dependent modulation of zingibain activity, as the acidic environment may partially inhibit this cysteine protease (He *et al,* 2015). Consequently, proteolytic potential is tempered while acid activated cathepsins remain active, producing balanced structural modification that preserves water holding capacity while still promoting tenderisation. The absence of significant correlations in the AG group, despite observable structural changes, suggests that multiple interacting mechanisms create heterogeneous responses that linear correlation may not capture. The 48 h treatment duration likely amplified these modifications, as marinating time strongly influences proteolytic and acid induced changes (Santos *et al,* 2020).

Collectively, these histological observations demonstrate that ginger and acetic acid exert their tenderising effects through distinct but complementary mechanisms. Interestingly, the dissociation between significant effects on cooking loss and colour parameters and the lack of statistically significant differences in histological measurements suggests that ginger and acetic acid marinades primarily affect meat quality through molecular-level modifications (protein denaturation, enzymatic hydrolysis) rather than through gross structural changes detectable at the fibre level.

This study characterised the individual and combined effects of ginger extract and acetic acid on some camel meat physicochemical and histological properties. Acetic acid alone induced pronounced acidification with moderate structural disorganisation but preserved water-holding capacity. Ginger alone exhibited effects consistent with proteolytic activity, increasing cooking loss and altering colour, with qualitative histological modifications despite non-significant quantitative changes. The combination treatment balanced these effects, achieving moderate acidification, preserved water-holding capacity, stabilised redness, and intermediate structural modifications. Quality modifications occurred primarily at the molecular level rather than through detectable fibre-level morphological changes. This finding advances beyond previous physicochemical-only assessments and provides mechanistic insight into tenderisation pathways. The combination treatment emerged as the most balanced formulation for potential industrial applications. These findings establish a scientific foundation for optimising camel meat quality and support sustainable protein diversification. Future research should validate sensory outcomes and optimise treatment parameters for industrial adoption.

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Author Contribution

Conceptualisation: SB. Methodology: SB. Investigation: SB and MHD. Data analysis: SB and MHD. Writing-Initial draft writing: SB, MHD, OB and HB. Editing, proofreading, and corrections: SB, MHD, HB and OB.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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