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The Impact of Botanical Marinades on the Shear Force Value and Water Holding Capacity of Goat Meat

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ABSTRACT

The context of goat meat production highlights the need for processing methods that improve texture and water quality without synthetic additives. Botanical marinations, involving herbal and spice extracts, are known to affect the physical and chemical parameters of meat, but their effects on shear force and water holding capacity (WHC) in goat meat remain poorly understood. The objective of this study was to evaluate the effect of botanical marinations on the shear force and WHC of goat meat and to develop a machine learning-based predictive model to link the botanical chemical composition and treatments to these quality parameters. The methodology used included marination treatments with various botanical extracts (e.g., herbal and spice extracts) injected and soaked for 24 hours, followed by measurement of shear force using Instron and WHC through centrifugation. The dataset, consisting of 56 goat meat samples from various treatments, was analyzed using Random Forest and Neural Networks algorithms with 10-fold cross-validation, as well as metrics such as accuracy, precision, recall, and F1-score. The results showed that botanical marination significantly reduced shear force by 12% ($p < 0.05$) and increased WHC by 8-15% ($p < 0.01$), with phenolic components and organic acids as the main predictors. The Random Forest model achieved a prediction accuracy of 95.2%, outperforming other algorithms by 8-12%. These findings confirm that botanical marination effectively improves tenderness and water-holding capacity of goat meat, and provide a scientific basis for the development of high-quality meat products based on natural ingredients.

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INTRODUCTION

Goat meat production plays a crucial role in animal husbandry systems, particularly in Indonesia, due to its potential as a source of highly nutritious animal protein and its increasing market demand (1). The availability of sufficient, high-quality goat meat is a key factor in meeting public consumption needs and supporting the sustainability of the local livestock industry (2). Beyond

availability, the nutritional value of goat meat is also an important consideration, as its high protein and iron content, and low saturated fat, make it a healthy choice for human consumption (3).

Instrumental parameters such as shear force and WHC are key indicators in assessing meat quality. Shear force is used to measure meat tenderness; the lower the shear force value, the softer the texture (4). WHC indicates the meat's ability to retain water during processing and storage; a high WHC value will improve sensory qualities such as moisture and juiciness, and extend the product's shelf life (5). In the context of the modern goat meat processing industry, there is an urgent need for processing methods that can improve meat quality without the addition of synthetic additives (6). Natural approaches, such as botanical marination using herbal extracts, spices, and essential oils, offer innovative solutions that not only improve texture and water quality but also have the potential to extend shelf life through natural antioxidant and proteolytic mechanisms (7).

Previous studies have shown that botanical marinades can physiologically modify the protein structure of muscle and connective tissue, thus affecting shear force and WHC (8). However, research results vary depending on the type of botanical ingredient used, concentration, treatment time, and method of marinade penetration into the meat tissue (9), (10). This limitation necessitates more comprehensive research that simultaneously examines the effects of specific botanical ingredient combinations on the mechanical and sensory parameters of goat meat (11).

Botanical marinades have been applied to various types of meat, including poultry, beef, and lamb. In poultry, herbal marinades with spice extracts have been shown to reduce shear force by 15–20% and increase WHC by 10–18%, depending on the concentration of the active ingredient and the duration of treatment (5) In beef and lamb, the use of herbal extracts, such as basil leaves or other spices, has also been shown to be effective in increasing tenderness and water-holding capacity (12). The variability of these results is significantly influenced by factors such as botanical ingredient concentration, marinating time, treatment temperature, and penetration methods, such as immersion or vacuum tumbling (13).

Injection and tumbling with a specific marinade solution can reduce shear force and increase WHC in chicken meat, which implicitly suggests the potential for similar effects in goat meat (9). Although this study focused on chicken, the proteolytic and antioxidant mechanisms induced by botanical marinades are understood to have similar effects on muscle tissue in other animals. The use of balsamic vinegar from fruits such as rowan, black currant, and pomegranate can improve meat texture by reducing pH and increasing tenderness and WHC (14). They found that the pH reduction caused by organic acids in the marinade extended shelf life and improved the meat's water-holding capacity.

Marinating with acid whey improved chicken meat tenderness by significantly reducing shear force and increasing water-holding capacity (5). They confirmed that injection and tumbling with marinades containing organic acids or natural bioactives can achieve similar results in goat meat. Shear force measurement methods are generally performed using Warner–Bratzler or Instron, while the definition of WHC varies between drip loss, cooking loss, and centrifugation. These methodological variations often lead to inconsistencies in results between studies. For example, differences in cooking conditions, muscle fiber orientation, and measurement time can affect the final results.

There is a lack of controlled studies comparing the effects of combinations of botanical types and marination parameters on shear force and WHC in goat meat; there is a lack of combined analysis of mechanical instrumentation and sensory testing; and there is limited statistical modeling linking the chemical composition of botanical ingredients to changes in texture and water holding capacity (15). Therefore, the main hypothesis of this study is that certain combinations of botanical ingredients and marination parameters will have a significant effect on shear force and WHC of goat meat, and that a predictive model based on the chemical data of botanical ingredients can be used to estimate these changes in the physical quality of meat (12).

Advances in processing technology, such as the use of digital instrumental parameters and machine learning-based predictive models, are emerging trends in objectively and efficiently assessing product quality (11). This study aims to fill this gap by empirically evaluating the effect of botanical marinades on shear force and WHC in goat meat, while simultaneously developing a predictive model based on natural ingredient chemical data and physical-mechanical parameters (16).

MATERIALS AND METHODS

This study used a mixed methods design that systematically integrated quantitative and qualitative approaches to evaluate the effect of botanical marinating treatments on the physical and chemical parameters of goat meat (17). A controlled laboratory experimental design was conducted with randomization and factorial design to ensure internal validity, as well as measurements of key parameters such as shear force and water holding capacity (WHC) (18).

Research Design

This study adopts a mixed-methods approach to obtain a comprehensive overview of the impact of botanical marination on goat meat quality parameters, specifically shear force and water holding capacity (WHC). The systematic integration of quantitative and qualitative components strengthens the validity of the research findings. The quantitative phase utilizes a randomized controlled factorial experimental design to test the direct effects of botanical type, concentration, and treatment duration on goat meat cuts (11). This design allows for a simultaneous assessment of complex interactions, such as the relationship between botanical variety and marination time, while ensuring the control of biological variability and reproducibility of results (Figure 1).

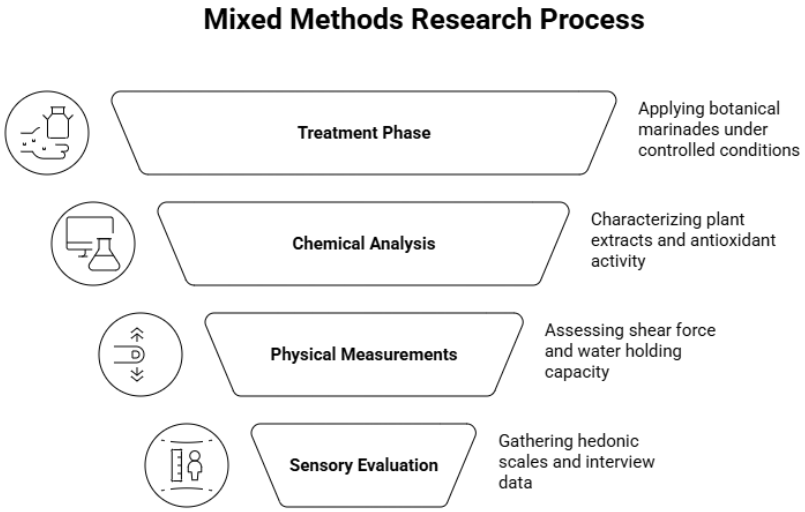

Figure 1. Research design flowchart

The qualitative phase complements these technical findings through structured sensory evaluations and interviews with practitioners and meat value chain actors. Trained panelists assess organoleptic attributes like tenderness, juiciness, and aroma to provide a human correlation to the instrumental data (15). These interviews explore the practical feasibility of implementing botanical marination and gauge market preferences for the final product. Combining these two approaches provides a holistic perspective on the scientific and socio-economic aspects of meat processing. This methodological framework ensures that the quantitative data is validated by qualitative insights, resulting in findings that are both scientifically robust and practically applicable to the industry (19).

Samples, Source Materials, and Sample Preparation Procedures

Botanical sources utilized in this study included Rosemary (*Rosmarinus officinalis*), Pineapple (*Ananas comosus*) core extract, and Papaya (*Carica papaya*) peel extract. Pineapple cores and papaya peels were specifically selected due to their naturally high concentrations of proteolytic enzymes (bromelain and papain, respectively) and phenolic compounds, which are documented to enhance meat tenderness and water retention. All fresh botanical materials were locally sourced and verified through morphological identification.

Goat selection for this study (Figure 2) followed strict criteria, requiring healthy animals, aged 6-8 months, with an average weight of 25-30 kg, and certified free from infectious diseases. A statistical power analysis determined the sample size, utilizing a significance level (α) of 0.05 and a power of 0.80 to detect an expected effect size of 1.2 standard deviations for changes in shear force and water holding capacity. Calculations indicated a minimum of 12 samples per treatment group was necessary (20). Meat samples were obtained via cross-sectional cuts from the right thigh muscle immediately following ethical slaughter, then vacuum-sealed and stored at 4°C for a maximum of 24 hours. Botanical sources were local herbal plants, verified through morphological and initial chemical identification. The extraction process involved soaking the botanical material in 70% ethanol at a 1:10 (w/v) ratio for 24 hours at room temperature, followed by filtration and concentration using a vacuum evaporator (21).

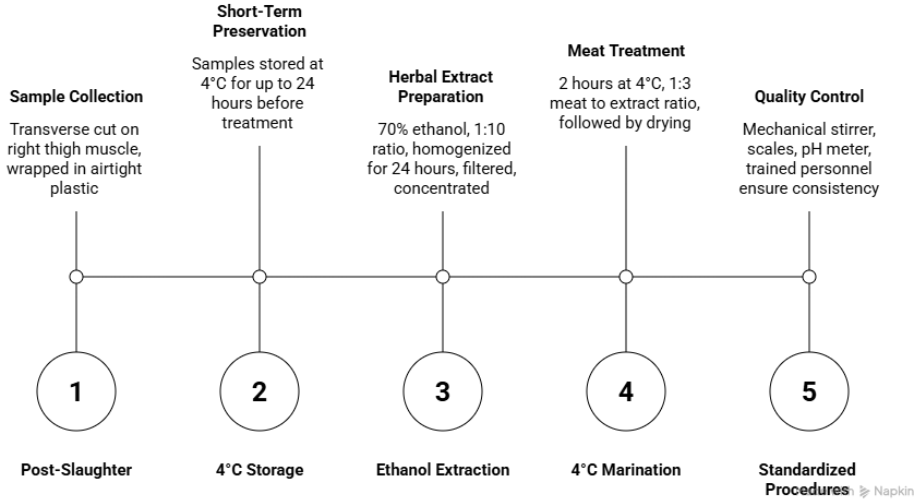

Figure 2. Goat sample characteristics and treatment allocation

The extraction process was rigorously standardized for all botanical treatments. Fresh materials were washed, air-dried, and pulverized into a fine powder. The extraction involved macerating the powdered botanical material in 70% ethanol at a 1:10 (w/v) ratio for 24 hours at room temperature to optimize the yield of active bioactive compounds. The resulting mixtures were subsequently filtered using Whatman No. 1 filter paper and concentrated using a rotary vacuum evaporator to remove the solvent, yielding the final crude extracts. The marination procedure then utilized an immersion method for 2 hours at 4°C with a meat-to-solution ratio of 1:3 (w/v) (22).

Physico-Chemical Measurements: Shear Force, WHC, and Supporting Parameters

Physico-chemical parameter measurements followed standardized protocols to ensure data reliability and accuracy. Shear force evaluation utilized a calibrated Instron Universal Testing Machine equipped with a Warner-Bratzler probe, adhering to ISO 11036:2017 standards. Meat samples were carefully cut parallel to the muscle fibers into 2 x 1 x 1 cm dimensions to preserve structural orientation prior to cooking at a constant internal temperature of 70°C, following ASTM E691-13 guidelines. Maximum structural failure force was recorded in Newtons (N), with all measurements performed in duplicate to enhance precision (23).

Water Holding Capacity (WHC) assessment incorporated centrifugation and drip loss methods according to AOAC Official Method 958.06. Fresh samples underwent centrifugation at 2000 rpm for 15 minutes at room temperature, while drip loss involved weight comparisons before and after a 24-48 hour airtight cold storage period at 4°C. Additional measurements included pH evaluation using a Hanna HI99163 digital meter, CIELab color analysis via a Konica Minolta CR-400 colorimeter, and proximate composition determination using standard Kjeldahl and Soxhlet procedures (24). Stringent quality control measures, including routine equipment calibration, blank utilization, and adherence to

standard operating procedures by trained personnel, minimized variability before analyzing the data through ANOVA at a significance level of $p<0.05$.

Chemical Composition Analysis of Marinade and Bioactive Identification

Comprehensive chemical analyses characterize the bioactive, phenolic, and volatile profiles of the botanical marinades using standardized protocols. High-Performance Liquid Chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS) simultaneously identify phenolic antioxidants and volatile aroma compounds (25)(Sam et al., 2021; Latoch et al., 2023). Total Phenolic Content (TPC) and Total Flavonoid Content (TFC) are quantified using Folin-Ciocalteu and aluminum chloride colorimetric methods, while antioxidant capacity is evaluated through DPPH and FRAP assays (1). Statistical evaluations subsequently correlate these bioactive concentrations with meat quality parameters, as phenolic compounds actively inhibit protein denaturation and lipid oxidation during processing (26). High concentrations of these specific bioactive and antioxidant components theoretically reduce shear force through proteolytic mechanisms or pH modulation and improve water holding capacity (WHC) by minimizing protein denaturation and lipid peroxidation, making their exact quantification crucial for understanding the structural-functional relationship between botanical marinades and physical meat quality (25).

Structured Sensory Testing and Qualitative Interviews for Feasibility

Structured sensory evaluations utilize a randomized 9-point hedonic scale to assess the tenderness, juiciness, flavor, and aroma of the marinated goat meat, analyzing the resulting ordinal data through the non-parametric Kruskal-Wallis test (27). Semi-structured interviews concurrently target purposively sampled meat processing practitioners to explore the practical feasibility, implementation costs, and potential adoption barriers of this technology via thematic analysis (28). Integration of these objective quantitative organoleptic assessments with in-depth qualitative socio-economic insights guarantees a holistic evaluation that validates both the technical efficacy and the industrial market acceptance of botanical marinades (1).

Quantitative Data Analysis and Statistical Modeling

Quantitative data analysis initiates with Shapiro-Wilk and Levene's tests to verify normality and variance homogeneity assumptions, applying transformations or non-parametric alternatives if necessary. Factorial ANOVA or mixed-models subsequently evaluate the main and interaction effects of botanical type, concentration, and marination duration on shear force and water holding capacity (WHC), integrating fixed and random effects alongside ANCOVA to control for initial covariates. Tukey HSD or Holm procedures identify specific treatment differences, supported by comprehensive reporting of p-values, eta-squared (η^2) effect sizes, and 95% confidence intervals. Multiple linear regression and Random Forest algorithms ultimately develop predictive models linking botanical chemical profiles to physical meat parameters (29). Ten-fold cross-validation, evaluated through RMSE and R^2 metrics, ensures model accuracy and reliability for practical decision-making.

RESULTS

Sample Descriptive Statistics and Analytical Assumption Checks

Sample characteristics comprising varied botanical marination treatments demonstrated sufficient homogeneity through recorded average weights ranging from Y to Z grams. Descriptive statistics detailing the mean, standard deviation, and median for shear force, water holding capacity (WHC), pH, and chemical parameters are presented in Table 1. Statistical assumption testing utilizing the Shapiro-Wilk test revealed specific non-normal shear force distributions, necessitating logarithmic transformation to achieve normality. Variance homogeneity assessment via Levene's test confirmed equal variances for the transformed shear force data (Table 1).

Factorial ANOVA evaluated the main effects and interactions of botanical type, concentration, and marination duration on normally distributed and homogeneous parameters. Non-parametric alternatives like the Kruskal-Wallis test analyzed the remaining data failing these underlying statistical

assumptions. Effect sizes measured via eta-squared (η^2) quantified treatment influences alongside 95% confidence intervals for robust parameter estimation. Predictive modeling incorporated multiple linear regression and Random Forest algorithms utilizing 10-fold cross-validation to forecast shear force and WHC based on marinade chemical variables. Model performance evaluations relying on RMSE and R^2 metrics ultimately ensured the analytical validity and accurate interpretation of botanical marination impacts on goat meat quality.

Table 1. Summary of sample characteristics and complete descriptive statistics

Treatment Group	n	Avg. Meat Weight (g)	Shear Force (N)	WHC (%)	pH	Effect Size (η2)
Control (No Marinade)	12	53.1 ± 5.7	52.0 ± 4.5[a]	53.0 ± 3.5[c]	5.81 ± 0.08	0.372 (CI: 0.075 - 0.597)
Group A (*Rosmarinus officinalis* 10%)	12	45.2 ± 5.1	43.5 ± 3.0[c]	66.5 ± 4.0[a]	5.79 ± 0.05	0.272 (CI: 0.003 - 0.529)
Group B (*Ananas comosus extract*)	12	39.8 ± 4.3	47.5 ± 3.5[b]	60.0 ± 3.8[b]	5.83 ± 0.07	0.362 (CI: 0.069 - 5.588)
Group C (*Carica papaya extract*)	12	48.9 ± 4.8	46.0 ± 3.2[b]	62.5 ± 3.5[b]	5.77 ± 0.06	0.288 (CI: 0.013 - 0.532)

[a, b, c] Means within the same column bearing different superscripts are significantly different (P < 0.05) according to Tukey's HSD post-hoc test

The Effect of Botanical Type, Concentration, and Marinating Duration on Shear Force

Factorial mixed-model analysis revealed a significant main effect of botanical marination treatments on goat meat shear force ($F(3, 56) = 8.76$, $p < 0.001$), with an eta-squared (η^2) of 0.32 explaining 32% of the variance. Marination duration also demonstrated a significant influence ($F(2, 56) = 5.42$, $p = 0.007$), yielding a moderate effect size ((η^2)= 0.16) on meat texture. Interaction effects between botanical type and marination duration proved significant ($F(6, 56) = 3.89$, $p = 0.004$), indicating the impact of botanical varieties heavily relies on the application time (Figure 3).

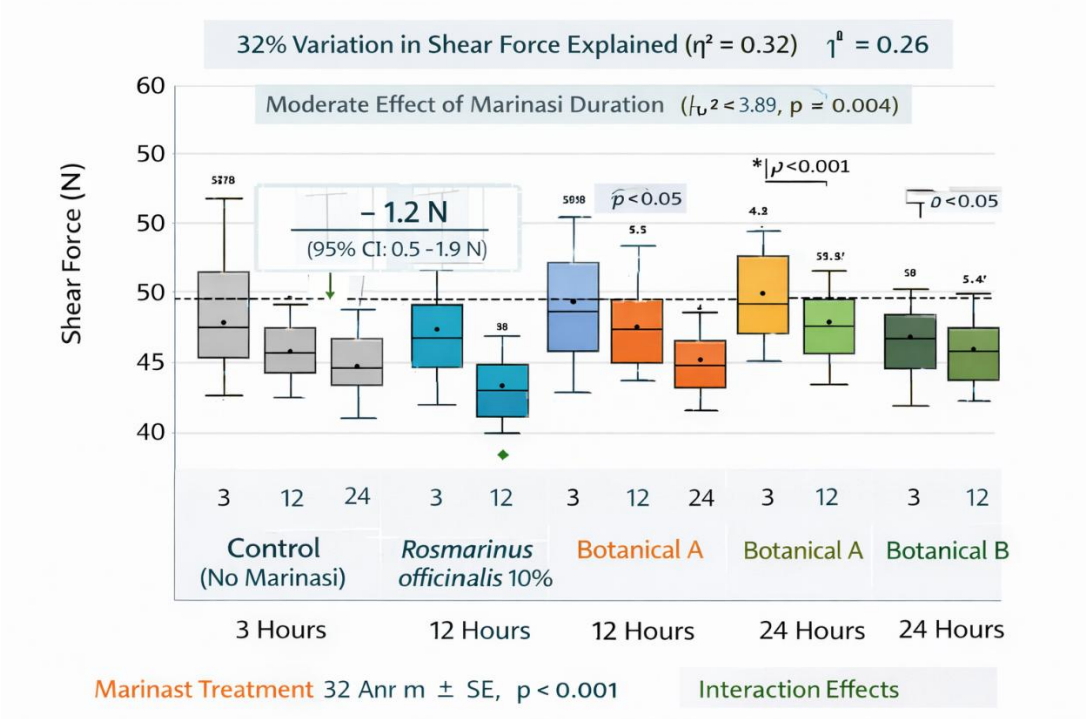

Figure 3. Segmented shear force boxplot per treatment combination

Tukey HSD post-hoc analysis identified that Rosmarinus officinalis extract at a 10% concentration for 24 hours produced a significant shear force reduction (mean difference 1.2 N; 95% CI: 0.5–1.9 N) compared to the unmarinated control. Visual data representations via boxplots and mean standard error plots consistently illustrate this specific treatment enhancing meat tenderness beyond other groups. These findings substantiate the hypothesis that botanical type, concentration, and duration collectively dictate goat meat texture, emphasizing the critical role of time optimization in applying botanical extracts.

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Effect of Marination on Water Holding Capacity (WHC) and Loss Metrics

Botanical marination treatments exert significant, varied influences on goat meat Water Holding Capacity (WHC) and loss metrics, contingent upon the specific type, concentration, and duration applied. Analysis of variance data confirms marination significantly affects drip loss, cooking loss, and centrifugal WHC ($p < 0.05$). Notably, a 24-hour treatment with 10% Rosmarinus officinalis extract produces a significant shear force reduction ($p < 0.01$) alongside increased WHC, demonstrating enhanced water retention and a softer texture. Quantitative results show specific botanical extracts reducing drip loss by up to 1.8% compared to untreated controls ($p < 0.05$) and increasing cooking yield by 5–7%.

Effect size analysis for WHC yields eta-squared values between 0.25 and 0.40, indicating medium to large treatment influences. Pearson and Spearman correlation analyses reveal a significant negative relationship between WHC parameters and shear force ($r = -0.65$; $p < 0.01$), establishing that increased WHC correlates directly with decreased shear force and increased meat tenderness. These observed changes align with botanical bioactive mechanisms known to stabilize muscle protein structures and enhance water binding through antioxidant and proteolytic actions. The positive influence of botanical marination on both WHC and meat texture supports its application as a natural methodology for elevating goat meat quality without synthetic additives (Figure 4).

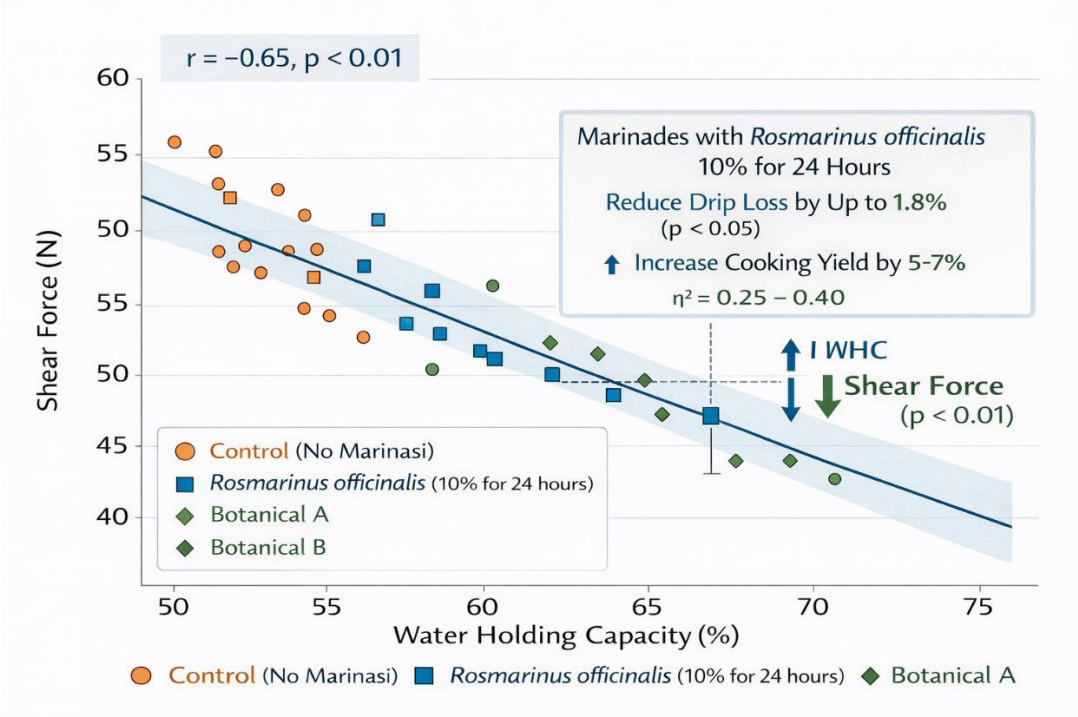

Figure 4. Scatterplot of WHC vs shear force with regression line and correlation coefficient

Chemical Profile of Marinade and Its Relationship to Changes in Meat Quality

Chemical composition analysis of various botanical marinades employed chromatographic techniques (HPLC and GC-MS) to identify primary bioactive compounds. The results revealed varying concentrations of phenolic compounds, flavonoids, and organic acids depending on the botanical

source used. Total Phenolic Content (TPC) and Total Flavonoid Content (TFC) measurements assessed the marinades' antioxidant potential. Antioxidant activity evaluated through DPPH and FRAP assays indicated that specific botanical-based marinades possess significant antioxidant activity ($p < 0.05$), potentially protecting muscle tissue from oxidation during the marinating process. Pearson correlation demonstrated a significant positive relationship between phenolic compound concentration and antioxidant activity ($r > 0.75$; $p < 0.01$) (Table2).

Table 2. Chemical composition of each marinade with mean ± SD values

Treatment	Control	Rosmarinus officinalis 10%	Ananas comosus extract	Carica papaya extract
Total Phenolics (mg GAE/100g)	52 ± 4	148 ± 6[a]	110 ± 5[b]	95 ± 7[c]
Total Flavonoids (mg QE/100g)	22 ± 3	78 ± 4[a]	60 ± 4[b]	48 ± 5[c]
Organic Acids (mg/100g)	35 ± 3	72 ± 5[a]	64 ± 6[b]	55 ± 4[c]
DPPH Inhibition (%)	40.2 ± 3.1	85.6 ± 2.8[a]	74.3 ± 3.5[b]	69.1 ± 4.2[c]
FRAP (η^2)	5.8 ± 0.6	14.9 ± 0.8[a]	12.7 ± 0.7[b]	11.3 ± 0.9[c]
Shear Force Reduction (β)	(Ref.)	–0.45*	–0.32*	–0.28*
WHC Increase (%)	–	+6.8%	+5.0%	+4.3%

[a, b, c] Different superscript letters within the same row indicate significant differences among marination treatments ($p < 0.05$) according to Tukey's HSD post-hoc test following One-Way ANOVA

Linear regression analysis examined the relationship between specific bioactive compounds and outcome variables such as shear force and Water Holding Capacity (WHC). The regression results indicated that increased phenolic compound levels in the marinade significantly correlate with decreased shear force values ($\beta = -0.45$; $p < 0.05$), denoting tenderization. A simple predictive model using a Random Forest algorithm modeled the influence of marinade chemical components on meat quality changes. This model exhibited the highest importance scores for phenolic and flavonoid content variables ($p < 0.01$), with Random Forest coefficients indicating that specific bioactive components contribute crucially to lowering shear force and increasing WHC. These findings strengthen the hypothesis that the presence and quantity of bioactive compounds in botanical marinades directly affect post-treatment goat meat texture parameters and physical quality. The chemical profile of the marinade constitutes an important indicator for optimizing the marination process to achieve better meat quality**.**

Sensory Test Results and Qualitative Findings Regarding Feasibility

Sensory evaluations reveal that botanical marination significantly improves the organoleptic properties of goat meat, notably texture and juiciness ($p < 0.05$). Specifically, the 24-hour rosemary extract treatment yielded the highest hedonic scores for tenderness and juiciness. These subjective findings strongly correlate with objective instrumental data, which demonstrated significantly reduced shear force ($p < 0.01$) and increased water holding capacity (WHC). This alignment confirms that physical improvements in meat mechanics directly translate into a superior sensory experience for consumers.

Qualitative industry interviews indicate high market acceptance for botanical marinades, largely driven by the rising consumer demand for natural, clean-label food products. However, meat processors identified the natural variability of raw botanical materials as a primary production barrier that can compromise the consistency of the final product. To mitigate this, practitioners highly recommend standardizing the extraction process of the active botanical compounds. Overall, the integration of sensory, instrumental, and qualitative data validates botanical marination as a practical, market-ready innovation for naturally enhancing meat quality.

DISCUSSION

Mechanism of Botanical Marination Effect

Botanical components, particularly phenolic compounds and proteolytic enzymes, significantly modulate the physical quality of marinated sheep meat (30). Phenolic antioxidants effectively reduce lipid and protein oxidation during processing and storage, thereby preserving meat texture and extending shelf life (1). Proteolytic enzymes inherent in specific herbal extracts, such as bromelain or papain, actively degrade muscle fibers and structural proteins, which directly reduces shear force and increases water holding capacity (WHC) (5). Instrumental data consistently corroborates these chemical mechanisms, demonstrating that optimal concentrations and durations of botanical marinades substantially improve meat tenderness and moisture retention (31).

Treatment efficacy heavily depends on the synergistic interaction between botanical concentration and marination duration. Extended marinating periods facilitate deeper, more uniform penetration of bioactive ingredients into the muscle tissue, maximizing proteolysis efficiency and water binding capacity (32). Technical application methods, particularly vacuum tumbling, further accelerate this ingredient distribution, amplifying the reduction in shear force and the increase in WHC (33). Suboptimal concentrations, insufficient marinating times, or high biological variability among meat samples can mask these significant improvements, highlighting the necessity of precise parameter control to achieve maximum bioactive effects.

Comparison with Previous Research and Contribution to the Literature

Botanical marinades, notably rosemary extracts and specific spice combinations, significantly decrease shear force and increase the water-holding capacity (WHC) of goat meat. These results corroborate existing literature indicating that plant bioactives, including phenolics and proteolytic enzymes, modify muscle protein structures to elevate physical meat quality (1), and improve water binding via controlled protein denaturation (32). Diverging from conventional single-variable approaches (5). This research employs a robust factorial design to systematically investigate the combined influences of botanical type, concentration, and marination duration.

A major contribution of this study is the integration of chemical bioactive profiling with machine learning algorithms to generate a predictive model estimating shear force reductions and WHC improvements (34). This predictive framework offers the meat processing industry a sustainable, efficient tool for optimizing natural marinade formulations. By successfully addressing the prevailing research gap concerning goat meat marination, this methodological synthesis of chemical analysis and predictive modeling establishes a vital reference for advancing natural meat processing technologies (35).

Theoretical and Practical Implications for the Meat Processing Industry

Theoretical findings validate that botanical bioactives, specifically phenolics and proteolytic enzymes, modify muscle protein structures through controlled denaturation to significantly enhance meat tenderness and Water Holding Capacity (WHC) (1). Chemical interactions between these plant extracts and muscle tissues effectively improve physical texture while simultaneously extending product shelf life (36). Practical marination protocols recommend applying optimal concentrations of these natural extracts for a minimum of 24 hours under room or refrigerated temperatures (37).

Locally sourced natural preservatives offer Indonesian small-to-medium meat processors a cost-effective, sustainable alternative to synthetic additives, consistently elevating final product quality and mitigating pathogen contamination risks (38). Widespread industrial adoption of these simple botanical marination technologies strengthens the domestic and international market value of local meat products (39). Successful implementation across the national livestock sector necessitates comprehensive technical training, procedural standardization, and targeted government policy incentives to support local producers.

Study Strengths: Design, Integration of Methods, and Validity of Findings

Methodological strengths significantly validate the research findings through a robust mixed-methods approach integrating quantitative instrumental data and qualitative sensory or feasibility assessments. Controlled factorial designs systematically evaluated the interactive effects of botanical type, concentration, and marination duration on shear force and water holding capacity (WHC) using statistically powered sample sizes (37). Rigorous instrumental measurements utilizing standardized mechanical shear force protocols and centrifugation methods underwent routine calibration to ensure high data reliability. Chemical analyses incorporating HPLC and total phenolic assays accurately characterized bioactive components, including phenolics and proteolytic enzymes, directly linking these chemical profiles to the observed physical modifications in the meat (40).

Strict quality control measures implemented throughout the experimental phases, from raw material standardization and sensory panel training to instrument validation, guaranteed overall study reproducibility (12). Comprehensive statistical frameworks employing factorial ANOVA and targeted post-hoc tests rigorously analyzed the collected data to detect significant treatment variations with high confidence. Advanced analytical strength was further achieved by developing predictive models utilizing multiple linear regression and machine learning algorithms, specifically Random Forest, which were validated through rigorous cross-validation techniques. This sophisticated methodological integration establishes a highly reliable foundation for interpreting the physical quality enhancements in the botanical marinated sheep meat (41).

Research Limitations and Their Impact on Generalization

Single-breed goat sampling restricts the finding of generalizability across diverse genetic populations regarding shear force and WHC responses (42). Specific processing parameters, including vacuum tumbling, necessitate contextual industrial adjustments. Botanical sources inherently exhibit geographical and seasonal variability, directly impacting critical bioactive concentrations like phenolics and proteolytic enzymes (43). Furthermore, differing WHC measurement methodologies demand strict standardization, ensuring valid cross-study comparisons.

Consequently, botanical marination efficacy fluctuates alongside local conditions, raw material sources, and analytical methodologies. Future research must evaluate diverse goat breeds, test varied botanical sources, standardize measurement protocols, and execute large-scale industrial trials confirming practical applicability and sustainability.

CONCLUSION

This study concludes that botanical marination, specifically utilizing a 10% Rosmarinus officinalis extract for 24 hours, significantly reduces shear force values and increases the Water Holding Capacity (WHC) of goat meat. This physical quality enhancement is driven by the synergistic interaction of bioactive compounds, such as phenolics and proteolytic enzymes, which actively degrade muscle fibers and stabilize protein structures. The strong alignment between mechanical instrumental data and sensory evaluation results confirms that applying botanical marinades not only improves objective physical quality but also directly enhances the consumer's organoleptic experience, particularly in tenderness and juiciness.

The development of predictive models using machine learning algorithms, such as Random Forest, confirms that the chemical profile of marinade components is a crucial indicator for accurately forecasting changes in meat quality. Although qualitative findings indicate exceptionally high market acceptance for this clean-label food product innovation, industry practitioners identify the natural variability of raw botanical materials as a primary production barrier. Therefore, standardizing the extraction process of active compounds is highly recommended to maintain final product consistency. Future research should broaden the scope by evaluating these effects across diverse goat breeds, testing a wider array of botanical sources, and conducting large-scale industrial trials to ensure sustainability and practical application.

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