



EFFECT OF THE MORINGA LEAVES EXTRACT ON THE TENDERIZATION OF *LONGISSIMUS* MUSCLE IN INDONESIAN NATIVE GOATS

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Keywords: *Moringa leaves extract, goat meat, cooking loss, proteolytic enzymes, tenderness*

Abstract

Meat tenderization techniques often involve time-consuming processes or chemical additives that may raise health concerns or alter the taste of meat. Exploring alternative natural methods, such as utilizing proteolytic enzymes derived from moringa, presents an opportunity to address these limitations. Studies on moringa have been limited, especially those focusing on goat meat tenderization, leaving a gap in understanding how moringa affects this process. The research aims to bridge this gap by systematically examining how protease enzymes from moringa leaves can tenderize goat meat. The research was performed on goat meat samples (100 g of meat per sample) treated with the moringa leaves extract (prepared from 20 g of moringa leaves with 60 ml of distilled water) at different storage times (2, 24, and 46 hours), as well as a control sample without any additive. The results showed that the moringa leaves extract did not significantly alter pH values and increased cooking loss for the 24-hour treatment (44.3%) and 46-hour treatment (39.8%) compared to the control (36.8%). Color analysis showed increased lightness (L^*) and redness (a^*). The yellowness (b^*) showed considerable difference between the control and the 24-hour samples compared with the 2-hour and 46-hour samples. The moringa leaves extract significantly reduced tenderness by lowering hardness, gumminess, resilience, and chewiness. This research advances environmentally friendly, renewable solutions in the food industry because the food industry produces significant quantities of meat by-products and waste during processing. This research will reduce waste by transforming tougher or less desirable meat cuts into more tender and valuable products.

For citation: Mohamed, T.H.A., Sumarmono, J., Fatoni, A., Setyawardani, T., Rahayu, S., Setyaningrum, A. et al. (2026). Effect of the moringa leaves extract on the tenderization of *Longissimus* muscle in Indonesian native goats.. *Theory and Practice of Meat Processing*, 11(1), 35–44. <https://doi.org/10.21323/2414-438X-2026-11-1-35-44>

Funding:

This research was supported by Jenderal Soedirman University through Professorship Research Grant No. 14.593/UN23.3/PT.01/V/2025 (May 14, 2025).

Introduction

Meat tenderness refers to the texture and softness of meat when it is cooked and consumed, and is an essential characteristic of meat quality that significantly affects the eating experience [1]. It is defined as the ease with which a product's structure can be disintegrated by the combination of shear, compression, and grinding actions during mastication. Tenderness is one of the most important quality parameters in consumer perceptions of meat [2]. In the tenderization process, the degradation of structural proteins in meat and collagen reduces meat toughness [3]. The production of consistently tender meat is crucial for retaining consumer confidence in red meat and maximizing financial gain, as tender meat cuts fetch a higher premium than less tender cuts. Several factors contribute to meat tenderness, including pre- and post-slaughter factors, such as the cut of meat, the animal's age, breed, diet, and the cooking method used. Over the years, the meat indus-

try has been continually searching for ways to improve meat tenderness, including ultrasound, high-pressure processing (HPP), wilting, electrocatalysis, and others. There is growing interest in exploring natural methods, such as the use of bacterial and plant enzymes, for meat tenderization. It has been shown that applying different types of bacterial enzymes, such as collagenolytic proteases derived from *B. subtilis* B13 and *B. siamensis* S6, to tenderize goat meat during wet aging decreased hardness, gumminess, and chewiness but increased springiness. Goat meat treated with these enzymes had shear force values that were 30% and 26% lower, respectively, than those of untreated samples [4]. Plant protease enzymes, such as papain, bromelain, ficin, actinidin, and zingibain, have been shown to improve the tenderness of meat due to proteolytic degradation [5]. Plant proteases can influence blood coagulation and may be used to treat digestive disorders [6]. Despite the benefits of using plant proteases in meat processing,

their application can present a challenge. If not appropriately used, they may over-tenderize meat, resulting in a mushy or undesirable texture. Plant proteases, depending on the specific enzyme used and the treatment duration, can affect meat flavor and aroma. Nevertheless, plant proteases have significant potential for various industrial applications.

Moringa is highly nutritious and contains essential amino acids, vitamins, and phenolic compounds. Moreover, it is widely distributed as a medicinal plant in tropical countries. *M. oleifera* (Moringaceae) is a tropical tree species with increasing utility, occurring naturally mainly in Pakistan and northern India. *M. oleifera* is currently cultivated in Africa, South America, Asia, and the Middle East. It is of high importance in the food pharmaceutical, cosmetic, agricultural industries. It has earned a few nicknames, such as 'the miraculous tree' and 'the tree of long life', and provides high-nutrient raw materials [7]. Studies on moringa have been limited, especially those focusing on goat meat, which are very scarce. Most existing research has focused on other types of meat and has also studied moringa as a supplement in animal diets. This left a gap in understanding how moringa affects the tenderness of goat meat. Thus, there is limited exploration of the biochemical mechanisms by which moringa contributes to meat tenderization, underscoring the need to understand the enzymatic activity and the impact of specific compounds in moringa that facilitate muscle fiber relaxation or collagen breakdown to provide valuable insights. Several studies have investigated the enzymatic properties of moringa protein and found that it contains proteolytic enzymes. Natural plant-derived extracts, such as those from *M. oleifera* leaves and seeds, have garnered interest as natural preservatives and functional additives, owing to their substantial antioxidant and antimicrobial properties, which can impede the proliferation of various pathogens, thereby enhancing food safety [8]. The presence of phytochemicals in the moringa, including flavonoids and other phenolics in its leaf extract, can hinder the growth of pathogenic microorganisms and extend the shelf life of food [9]. The study found that the moringa leaves extract exhibited potent antimicrobial activity against spoilage bacteria, including aerobic plate count and Enterobacteriaceae counts, and reduced counts of *E. coli*, *Salmonella enterica* serovar Typhimurium, and *Staphylococcus aureus* artificially inoculated into ground beef [9]. Nevertheless, this purified enzyme can be considered a promising agent, a cheap and safe source suitable for various industries [10]. Moringa extracts contain a wealth of bioactive compounds, including flavonoids, phenolic compounds, and antioxidants, which have garnered attention for their potential use in meat and meat products [11]. Mashau et al. [12] found that adding moringa leaves powder to ground beef improved its nutritional properties and inhibited lipid oxidation. Moringa leaves have been found to significantly enhance the tenderness of goat meat, especially in the *Longissimus* muscle, by making it more tender

when using moringa leaves as a paste [13]. Adding the moringa leaves extract improved tenderness in beef patties, with a 2% extract level yielding the best results in terms of protein and fat content and sensory quality [14]. In addition to tenderness, moringa leaves also improve meat aroma without compromising color or taste. This was evident in the Bali beef, which was marinated with moringa leaves powder and received better overall acceptance from taste testers [15]. Moringa leaves are a treasure trove of nutrients and bioactive compounds, providing antioxidant and antimicrobial benefits that lead to healthier meat products [16]. Kenawi et al. [17] utilized moringa as a natural antioxidant to investigate its impact on the quality of buffalo meat products. It was demonstrated that the moringa leaves extract exhibited an inhibitory effect on bacterial growth and enhanced the acceptability of the meat product. Moringa extract acts as an antioxidant, helping maintain meat quality during storage and indirectly affecting its texture by preventing oxidative rancidity [18]. Bioactive compounds in moringa have antimicrobial and antioxidant properties that can enhance meat preservation and safety by reducing microbial growth and oxidative stress [16]. Moreover, other studies have demonstrated that moringa can help modulate the gut microbiota of broilers by promoting the establishment of beneficial microorganisms while inhibiting harmful pathogens, thereby further supporting meat quality and safety [19]. Mwankunda et al. found that meat samples treated with a 1.5% crude extract of moringa leaves had significantly improved pH, juiciness, texture, flavor, taste, and overall acceptability scores compared to the control and other treated samples [20]. Abubakar et al. [21] concluded that marinating African catfish with a combination of moringa leaves and ginger rhizome significantly improved the proximate and sensory qualities of the fish. Moringa leaves powder increased the protein content in meat, particularly in the thigh and breast muscles, while at the same time reducing fat levels in broilers [22]. The inclusion of moringa also lowered the cholesterol and triglyceride levels in meat, leading to a healthier meat product [19]. Using moringa leaves in meat processing could also help tackle food security and sustainability issues, thanks to its resilience and rapid growth, making it a promising option for improving meat quality [16]. The moringa leaves extract enhances meat quality by increasing the antioxidant activity and protein content, reducing fat content, altering pH levels, and improving consumer preference when unpleasant odors are removed, contributing to better nutritional and sensory properties [23].

Ultimately, research on improving the tenderness of goat meat using moringa leaves can significantly contribute to both academic knowledge and practical applications in the meat industry. Enhancing the quality of goat meat through natural additives such as moringa can increase farmers' productivity and profitability, supporting local economies and food systems. By improving the tenderness and overall quality of goat meat, moringa supplementation

can potentially lead to better consumer health outcomes. As a natural additive, moringa may reduce the reliance on synthetic tenderizers, thereby contributing to safer food products for consumers. Moringa is a natural additive that reduces the need for synthetic tenderizers or antibiotics, leading to safer food products for consumers. Moringa leaves can be sourced from local agricultural practices, reducing waste and promoting a circular economy within livestock production. The primary purpose of this research is to enhance the tenderness of goat meat using the natural proteolytic enzyme derived from moringa leaves. Moreover, the extraction of this enzyme could be economically viable and environmentally friendly, as it is derived from natural sources. The analysis yielded new data on how moringa affects various physical, chemical, and textural attributes, including pH, color, cooking loss, and textural properties such as hardness, chewiness, springiness, and overall mouthfeel, which are critical to consumer acceptance. The parameters studied include cooking loss, texture profile, acidity (pH), and color.

Objects and methods

Objects

The primary research material consisted of goat meat, collected from approximately one-year-old male goats, specifically the *Longissimus dorsi* muscle, which was taken between the 9th and 12th ribs on both the left and right sides, totaling 1200 g of muscle samples (6 pieces of *Longissimus dorsi* muscle, each was 200 g, each piece was divided into two pieces of 100 g to use as one replicate). These samples were collected from six goats. They were obtained from a meat shop after slaughter, transported to the lab, stored in the freezer (-19°C) for one week, and then used. The study was conducted in the Animal Products Technology Laboratory, Faculty of Animal Sciences, and the Biochemical Laboratory, Faculty of Mathematics and Natural Sciences at Jenderal Soedirman University, Purwokerto,

Indonesia. Moringa leaves were obtained from a farm near Jenderal Soedirman University.

The preparation of the moringa leaves extract

Twenty grams of moringa leaves (for each sample) were weighed, washed, and then ground using a mortar and pestle. The ground leaves were mixed with 60 mL of distilled water and stirred using a magnetic stirrer (Thermolyne Cimarec 3 hotplate stirrer, Model SP47235, Thermo Fisher Scientific, US) for 30 minutes at 4°C . The mixture was then filtered using a cloth and centrifuged at 7000 rpm for 10 minutes (BIOBASE, Model BKC-TH23RII, BIOBASE Group, China). The supernatant was used to marinate meat samples. The process of the moringa leaves extract preparation is illustrated in Figure 1.

Protease activity

Protease activity was assayed using casein as a substrate. A total of 0.5 mL of casein solution was preincubated (Lab-Line, Model Aquabath, Lab-Line Instruments Inc, US) at 35°C for 5 min, after which 0.1 mL of crude enzyme extract was added. The mixture was incubated at 35°C for 30 minutes, and the reaction was stopped by adding 4.3 mL of 1 M HCl, resulting in a final volume of 4.9 mL. Samples were kept at 4°C for 30 minutes and then centrifuged at room temperature for 10 minutes to remove undigested protein (LD-3 Electronic Centrifuge, maximum speed 4000 ppm, YJNGUI China). The absorbance of the supernatant was recorded at 275 nm using a Spectrophotometer (Shimadzu Corporation, Model UV-1280, Japan). Tyrosine was used as the standard, with the calibration curve described by the Equation.

$$y = 0.0232x - 0.0073, \quad (1)$$

where y is the absorbance; x is the tyrosine concentration (mg/L).

One protease unit (U) was defined as the amount of enzyme that releases one μmol of tyrosine per minute under the assay conditions.

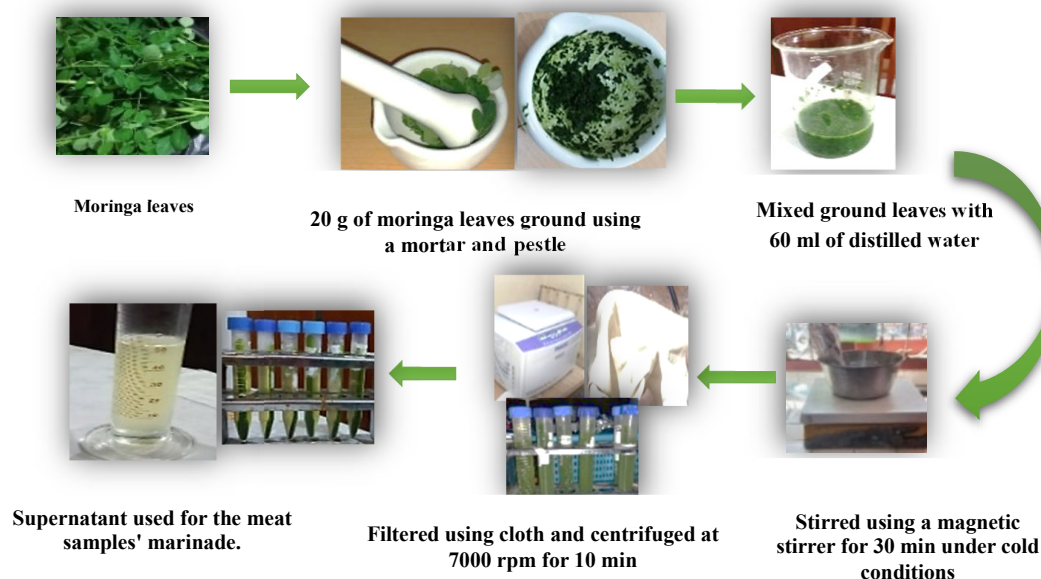


Figure 1. The process of preparing the moringa leaves extract

Phytochemical test (alkaloids, flavonoids, and tannins)

Phytochemical screening was carried out to identify alkaloids, flavonoids, and tannins in leaves extracts. Alkaloids were detected using Dragendorff’s reagent, which yields a characteristic green, brown, or orange-red precipitate. Flavonoids were tested with a 5 % aluminum chloride solution, which produced a yellow to green coloration or a precipitate in the presence of flavonoid hydroxyl groups. Tannins were identified using ferric chloride (FeCl₃), which gives a dark green, purple, or black color when tannins are present.

Meat sample preparation

The meat samples were divided into four treatments (each 100 g) with three replications: T0 (control without additives), T1 (marinated for 2 hours), T2 (marinated for 24 hours), and T3 (marinated for 46 hours). The samples were marinated in the moringa leaves extract, ensuring that they were fully covered. They were stored in glass containers and put in the refrigerator at different times (2, 24, and 46 hours). The samples were analyzed for pH, color, cooking loss, and texture profile. The tenderization of the meat samples using the moringa leaves extract is shown in Figure 2.

pH determination

The measurement was performed by dipping a calibrated pH meter ((pH meter (Portable pH Meter HI8424, Hanna Instruments, USA) into a homogenized meat mixture. All measurements were performed at room temperature.

Cooking loss (CL)

Three cubes were cut from each sample, weighed, placed in labeled plastic bags, and subsequently cooked in a water bath (Mettler Water Bath WTB11, Mettler GmbH, Germany) at 80 °C for 10 minutes. Next, the cooked muscles were chilled, blotted dry, and weighed using a scale (AND GF Series, A&D Technology, Japan). The cooking loss percentage (CL%) for each sample was then calculated using the following formula, adapted from [24]:

$$CL(\%) = \frac{\text{Initial Sample Weight} - \text{Sample Weight After Cooking}}{\text{Initial Sample Weight}} \times 100, \quad (2)$$

Texture profile analysis

Texture profile analysis of meat was performed using a Food Texture Analyzer (TA-XT, Stable Micro Systems, Godalming, UK). An aluminum cylinder probe with a diameter of 40 mm was used. The experiments were conducted at room temperature under a 30 % compression ratio and crosshead speeds of 1.0 mm/s and 2.0 mm/s. Meat samples were cut into uniform pieces to ensure homogeneity and then placed between the probe and the base. Parameters measured included hardness, springiness, cohesiveness, chewiness, gumminess, resilience, firmness, and adhesiveness.

Color

The colorimetric evaluation of treated and control samples included the colorimetric parameters L* (lightness), a* (green to red coordinate), and b* (blue to yellow coordinate) using a Konica-Minolta CR-400 colorimeter (Konica-Minolta, Japan).

Statistical analysis

The obtained data were statistically analyzed using the SPSS program for Windows (Version 25) and tested using one-way ANOVA, followed by Duncan’s multiple range test to compare means. Data are expressed as mean values ± standard deviation (SD). The accepted level of significance for all comparisons was *p* < 0.05.

Results

Protease activity

Protease activity assays demonstrated measurable casein hydrolysis by the leaves extract. The crude leaves extract produced an absorbance of 0.510 at 275 nm, equivalent to 22.30 mg/L tyrosine. After subtracting the control (0.126, 5.74 mg/L), the net release was 16.56 mg/L, corresponding to 0.449 μmol tyrosine. This yielded an activity of 0.015 U in 0.1 mL of enzyme extract, corresponding to 0.15 U/mL in the crude extract.

Phytochemical test

Qualitative phytochemical screening revealed that leaves extract of moringa tested positive for alkaloids, flavonoids, and tannins. Distinct color changes and

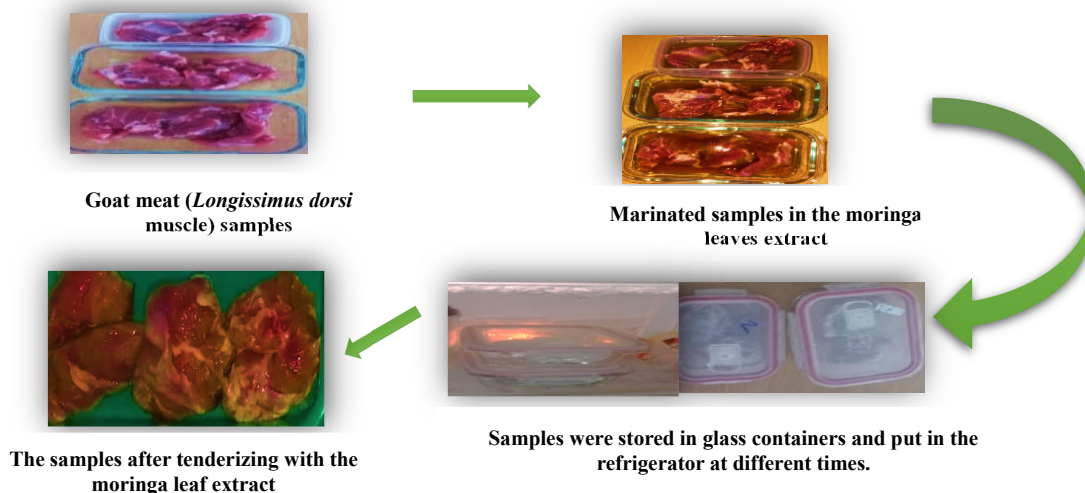


Figure 2. Tenderization process of goat meat samples with the moringa leaf extract

precipitate formation confirmed the presence of these secondary metabolites. These results are consistent with previous findings that moringa tissues contain abundant phytochemicals, which contribute to their antioxidant and antimicrobial potential.

Effects of the moringa leaves extract on the texture profile analysis of goat meat

Table 1 shows the texture profile analysis (TPA) parameters of the treatments (T0 (control), T1, T2, and T3) from *Longissimus* muscle treated with the moringa leaves extract and stored for different durations (0-hour [control], 2-hour, 24-hour, and 46-hour) at a temperature of 4°C. There was a significant difference ($p < 0.05$) between the control and treated samples, in hardness, as the hardness decreased from (4720.3 ± 2354.28) in the control to (451.04 ± 301.75 , 335.96 ± 122.92 , and 1013.56 ± 739.11) in the samples treated for 2, 24, and 46 hours, respectively. There was a significant difference ($p < 0.05$) between the treated and control samples in gumminess, resilience, and chewiness, with lower values in the treated samples than in the control. There was no statistically significant difference between the treated samples and the control samples in springiness, cohesiveness, firmness, or toughness.

Effects of the moringa leaves extract on the pH and cooking loss of goat meat

Figure 3 and Table 2 show no significant differences in pH between the control samples compared to the 2-, 24-, and 46-hour treatments. Figure 4 and Table 2 show that the treated samples have increased cooking losses compared to the control samples, except for the 2-hour treatment. The cooking loss for the 24-hour treatment was significantly higher than that of the control and the other treatments, increasing from 36.8% to 44.3%.

Effects of the moringa leaves extract on the color of goat meat

Figure 5 shows a significant difference between the control and the treatments in lightness; however, no significant difference was observed among the treatments themselves. There was no significant difference in redness between the treated samples and the control. Also, there was no significant difference between the control and the 24-hour samples, nor between the 2-hour and the 46-hour samples, in terms of yellowness. However, there was a considerable difference in yellowness between the control and the 24-hour samples, as well as between the 2-hour and 46-hour samples.

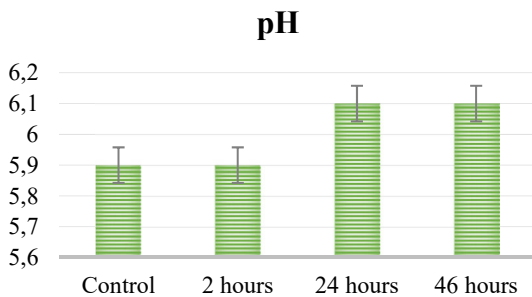


Figure 3. Effects of the moringa leaves extract on the pH of goat meat during different aging periods

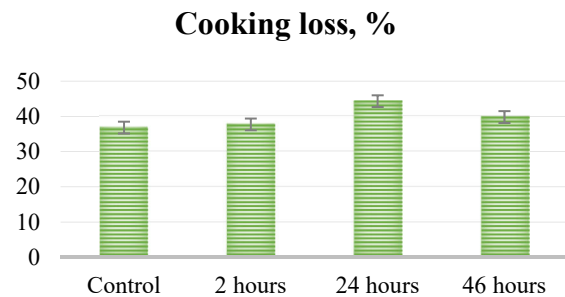


Figure 4. Effects of the moringa leaves extract on the cooking loss of goat meat during different aging periods

Table 1. Texture profile analysis (TPA) of goat meat treated with the moringa leaves extract during different aging periods

Item	Control	Tenderization period, hr.		
	0	2	24	46
Hardness, g	4720.31 ± 2354.28 ^a	451.04 ± 301.75 ^c	335.96 ± 122.92 ^c	1013.56 ± 739.11 ^b
Chewiness, mJ	1057.01 ± 670.87 ^a	120.92 ± 96.15 ^b	93.13 ± 55.40 ^b	170.80 ± 118.00 ^b
Firmness	3971.56 ± 885.95 ^a	4687.14 ± 2026.85 ^a	3220.38 ± 506.77 ^a	3663.77 ± 1919.00 ^a
Toughness	25448.59 ± 5561.73 ^a	27071.39 ± 13227.14 ^a	19019.55 ± 2222.62 ^a	19388.06 ± 8790.85 ^a
Adhesiveness, mJ	-47.17 ± -47.17 ^b	-15.02 ± 15.24 ^a	-26.44 ± 26.12 ^{ab}	-21.88 ± 13.14 ^{ab}
Gumminess, g	1886.87 ± 959.17 ^a	209.90 ± 130.00 ^b	162.09 ± 69.15 ^b	396.44 ± 309.90 ^b
Cohesiveness	0.40 ± 0.08 ^a	0.50 ± 0.10 ^a	0.47 ± 0.05 ^a	0.40 ± 0.09 ^a
Springiness, mm	0.54 ± 0.14 ^a	0.52 ± 0.12 ^a	0.56 ± 0.15 ^a	0.48 ± 0.10 ^a
Resilience	0.24 ± 0.06 ^a	0.20 ± 0.05 ^{ab}	0.16 ± 0.04 ^b	0.17 ± 0.03 ^b

Different letters (a, b, c) in the row indicate significant differences between means ($p < 0.05$).

Table 2. PH and cooking loss of goat meat treated with the moringa leaves extract during different aging periods

Item	Control	Tenderization period (hr.)		
	0	2	24	46
PH	5.9 ± 0.2 ^a	5.9 ± 0.7 ^a	6.1 ± 0.2 ^a	6.1 ± 0.4 ^a
Cooking loss (%)	36.8 ± 1.6 ^b	37.7 ± 4.2 ^b	44.3 ± 1.4 ^a	39.8 ± 6.1 ^{ab}

Different letters (a, b, c) in the row indicate significant differences between means ($p < 0.05$).

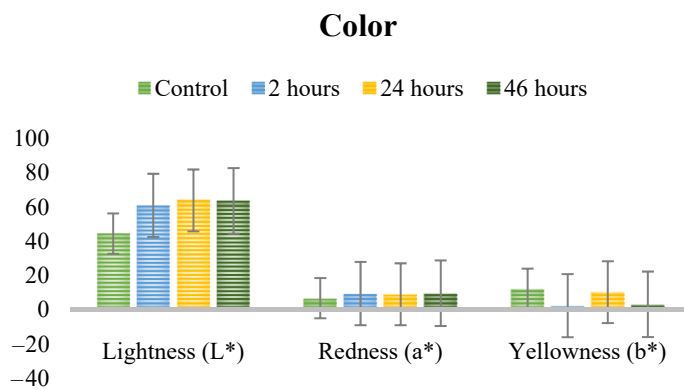


Figure 5. Effects of moringa leaves extracts on the color parameters of goat meat during different aging periods

Discussion

Protease activity

The protease from moringa leaves had a molecular weight of approximately 51 kDa and was classified as a cysteine protease based on its inhibition by HgCl_2 [25]. The proteases showed high specificity for casein, with additional activity on whey and gelatin. They were stable at temperatures between 40–60°C and pH levels of 4–7 [25,26]. Future work should include protein quantification, kinetic studies, and characterization of pH and temperature optima. Together, these findings demonstrate that leaves of *Moringa oleifera* are promising sources of proteolytic enzymes and phytochemicals, supporting their potential applications in food processing, nutraceutical, and biotechnological industries.

Phytochemical test

M. oleifera, frequently referred to as the drumstick tree, is distinguished for its extensive phytochemical profile and protease activity, which are integral to its multifaceted medicinal attributes. The foliage and seeds of moringa are rich in alkaloids, flavonoids, and tannins, which are pivotal phytochemicals with a range of health-promoting effects. These bioactive compounds are recognized for their antioxidant, antimicrobial, and anti-inflammatory capabilities, rendering moringa a significant botanical resource in both traditional and contemporary medicinal practices. While moringa is lauded for its rich phytochemical composition and protease activity, it is essential to acknowledge the variability of these compounds, which depends on the extraction methodologies used. Such variability can significantly affect the effectiveness and potency of moringa-derived products, underscoring the need for standardized extraction and analytical protocols to ensure consistent outcomes. The presence of flavonoids, alkaloids, and tannins in leaf extracts highlights the multifunctional nature of moringa bioactive components, in agreement with the studies by Ogah et al. [27] and Arbab et al. [28], who found that preliminary phytochemical screening of leaves extracts revealed the presence of alkaloids, tannins, flavonoids, and saponins. Alkaloids found in the leaves of the moringa contribute to its pharmacological functions, including anti-

inflammatory and analgesic properties [29,30]. The leaves of moringa are particularly rich in flavonoids, which are efficacious antioxidants that help scavenge free radicals, thereby alleviating oxidative stress and inflammation [31]. The tannins present in moringa are recognized for their astringent properties, which can facilitate wound healing and reduce inflammation [32]. They also exhibit antimicrobial properties, thereby enhancing moringa's efficacy in treating infections and promoting gastrointestinal health [29]. Additionally, the presence of various bioactive compounds contributes to its antimicrobial properties [33], antioxidant benefits, and may also influence enzyme stability or interactions with substrate proteins.

Effects of the moringa leaves extract on the texture profile analysis of goat meat

In the current study, statistical analysis showed that leaves extract significantly decreased ($p < 0.05$) the textural properties of hardness, gumminess, resilience, and chewiness; the other attributes, including springiness, cohesiveness, adhesiveness, and resilience, showed no significant differences between treated and control samples. Some of the studies suggest that moringa leaves can act as a natural tenderizer, improving the texture profile analysis (TPA) of goat meat. Mohamed et al. [13], stated provided that moringa leaves paste, when applied for 3 to 6 hours, leads to a substantial difference in textural properties such as hardness and gumminess in goat meat. The findings of Botinestean et al. [34] indicate that specific cuts of meat can exhibit resistance during mastication. This resistance can lead to oral discomfort, particularly for elderly consumers, which may deter them from consuming meat. Rahman et al. [35] demonstrated a significant increase in tenderness and overall acceptability when using *M. oleifera* leaves extract on goat meat nuggets, which agrees with the findings of the current study. Thus, moringa leaves can offer a solution to enhance meat tenderness and improve overall consumption experiences for this demographic. Tender steaks often come with a high price tag, limiting access for many consumers. The changes in hardness observed with moringa indicate its potential to enhance meat softness, thereby significantly improving the sensory experience during consumption. This finding aligns with Rizqiati et al. [36], who reported a marked increase in softness in raw samples treated with papain. Additionally, the observed changes in chewiness and firmness suggest that moringa facilitates the breakdown of meat fibers, making it easier to chew. Alterations in firmness also play a critical role in overall mouthfeel and the eating experience. This is supported by Kakash et al. [37], who found that marinating chicken thighs in kiwi protein for varying durations at $4 \pm 1^\circ\text{C}$ improved chewiness and reduced hardness. Their study highlighted that the duration of enzyme exposure significantly affected the degradation of meat proteins, similar to the effects noted with the moringa treatment. The 0.5% concentration of protease from the Biduri

plant has been shown to significantly reduce compression and tensile strength values, indicating enhanced tenderness [38]. The tenderizing effect is attributed to proteolytic enzymes and other bioactive compounds in plants that interact with muscle proteins during marination, leading to their breakdown and enhanced tenderness [39]. Empirical evidence supports this, showing that the moringa leaves extract improves textural attributes, juiciness, and overall acceptability in ground beef [20]. Adding moringa oleifera not only improves texture but also enhances the nutritional content by raising protein levels and antioxidant activity in meat products [22]. Plant proteases, such as papain and bromelain, degrade muscle proteins, reducing shear force and imparting tenderness [40,41]. However, excessive proteolytic activity can quickly tenderize meat, leading to a mushy or unacceptable texture that consumers dislike [40]. This requires control of enzyme concentration and duration for optimal meat quality.

Effects of the moringa leaves extract on the pH and cooking loss of goat meat

The current study found that there was no effect of the moringa leaf extract on the pH in the treated samples when compared to the control. This is the opposite of what was reported by Mohamed et al. [13], who found that the moringa leaf paste increased the pH of goat meat samples. The difference between two studies may be due to the difference in the amount of moringa leaves, as well as in the time and method of treatment applied in these studies. Das et al. [18], concluded that the moringa leaf extract did not significantly influence the pH of raw and cooked goat meat patties. This result is in close agreement with the current study. In addition, Moyo et al. [42] indicated that the dietary supplementation of moringa leaf meal did not significantly affect the pH of goat meat compared to different diets, such as grass hay or sunflower seed cake, at 24 hours post-mortem. Thus, these studies demonstrate that there is a possibility of improving meat quality sometimes without causing a significant change in pH as moringa leaves contain phenolic compounds, which have antioxidant activity, and enzymes that affect the tenderness of meat.

The results obtained in the current study show that even though the moringa leaves extract did not directly affect pH, it indirectly affected other nutritional qualities, such as color and texture, ultimately improving overall meat quality. However, the treated samples exhibited higher cooking losses than the control samples, except for the 2-hour treatment. The cooking loss for the 24-hour treatment was significantly higher than that of the control and the other treatments, increasing from 36.8% to 44.3%. These results indicate that marination time was a key factor in determining cooking loss, with the lowest values at 2 hours, peaking at 24 hours, and then declining at 46 hours. This is interpreted as resulting from extensive proteolysis at 24 hours, which weakens the meat water-holding capacity. At 46 hours, partial protein restabilization may occur,

reducing further water loss. Applying moringa as a natural tenderizer not only can improve the texture but also can increase cooking yield, preventing moisture loss during cooking [13]. The stable pH range (5.9–6.1) observed in the present study, despite the addition of moringa extract, can be attributed to the inherent buffering capacity of the meat system, as well as to the concentration of moringa extract used, which may not be sufficient to significantly alter the pH of meat. Moringa extracts contain high concentrations of phenolic compounds and flavonoids [11]. Apriantini et al. [23] reported that the moringa leaves extract affected the pH of goat meat, leading to increased cooking loss. Das et al. [18] have not found a significant difference in cooking yield between the control and treated patties using the moringa leaves extract, indicating a minimal impact on cooking loss. On the other hand, despite the promising outlook for moringa in improving meat quality, excessive application would impair water-holding capacity and cooking yield [14]. The effects of moringa extracts on cooking loss can be compared with those of other plant-based additives to assess the specificity of these interactions. Studies on marination with Citrus aurantifolia juice showed variable effects on cooking loss in chicken breast meat, depending on concentration and marination time [43].

Effects of the moringa leaf extract on the color of goat meat

The chromatic characteristics of meat are a critical element in the meat industry, as they profoundly shape consumers' perceptions of product quality and thereby significantly influence purchasing decisions [44]. The use of the moringa leaves extract in this study resulted in increased lightness of the treated samples compared to the control. This result may be attributed to increased water loss, which improves light reflectance due to the proteolytic enzyme in moringa that enhances lightness by altering protein structure. In the study by Mohamed et al. [13], moringa leaves were not found to be effective in improving lightness, which is inconsistent with the current research. The antioxidative properties of moringa may also help maintain color stability during storage and reduce oxidative changes that cause discoloration [18]. In the present investigation, a discrepancy in redness was observed between the treated samples and the control group; however, this difference was not statistically significant. This phenomenon may be attributed to the antioxidants present in moringa, which could have preserved myoglobin stability, thereby averting discernible changes in redness. Feihrmann et al. [45] noted that moringa extracts did not significantly influence the visual coloration of beef samples, which aligns closely with the results of the current study. In this study, no statistically significant differences were observed between the control and the 24-hour samples, nor between the 2-hour and 46-hour samples, with respect to yellowness; however, a noteworthy difference was identified between the control and the 24-hour samples and between the 2-hour and

46-hour samples. Mwankunda et al. [20] found that the values of lightness (L^*), redness (a^*), and yellowness (b^*) exhibited a significant reduction upon the application of moringa. In the study by Mohamed et al. [13], yellowness exhibited an increase, thereby enhancing the overall color profile. Comparable results were reported, showing that when using proteolytic enzymes from ginger and papaya, collagen and myofibrillar proteins, improved tenderness and the appearance of the goose breast cut became lighter likely due to the breakdown of darker muscle fibers [46]. Enzymes derived from ginger and papaya resulted in from the breakdown of proteins, reducing toughness and improved color in goat meat [5]. It is crucial to note that the documented color alterations did not adversely affect overall quality; instead, they may enhance consumer acceptance by increasing visual appeal. Although the moringa leaves extract demonstrated a beneficial impact on the color and quality of goat meat in this investigation, it is crucial to acknowledge that consumer acceptability will likely fluctuate based on additional sensory attributes, particularly flavor, which is also contingent upon the preparation methods, the quantity of moringa extract utilized, and the duration of storage.

Conclusion

The current research investigated the tenderizing efficacy of moringa leaves on Indonesian goat meat (*Longissimus dorsi*) across varying marination durations. This research has established that moringa leaves exhibit con-

siderable potential as a natural tenderizer for goat meat and significantly enhance meat tenderness by markedly reducing specific texture attributes, while maintaining pH within acceptable limits. Aqueous leaves extracts, when applied for 2 hours, demonstrated substantial tenderizing effects. However, extending the marination duration to 24–46 hours increased cooking loss and, in some instances, negated the tenderness benefits due to excessive protein degradation. Overall, the moringa leaves extracts are promising, environmentally friendly, and health-conscious alternatives to synthetic tenderizers. This research concluded that the moringa leaves extract has a promising future in meat tenderization, given the optimal treatment period and the amount of the extract applied. This finding opens a broad field for further research into the optimal amount of the moringa leaves extract and treatment duration for tenderizing meat. In summary, taking into account the sustainability development goals of this study, investigating moringa as a sustainable alternative to synthetic tenderizers aligns with current trends toward natural food additives to attract interest from both consumers and producers focused on sustainable practices. In addition, given that goat meat is a staple in many cultures, particularly in developing regions, exploring practices of using moringa could provide culturally relevant insights into improving meat quality while respecting traditional methods. The findings from this study on the tenderization of goat meat can be extrapolated to other ruminants, broadening the impact on livestock management practices across species.

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The authors declare no conflict of interest.