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REVIEW

Quality Enhancement Techniques for Cow Meat: Current Approaches and Future Directions

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Abstract The quality grade of cow meat is often lower than that of steer meat, resulting in economic losses and reduced consumer satisfaction. This review explores various strategies for improving the quality of cow meat, with a focus on slaughter and post-slaughter practices. Certain slaughter methods, including electrical stimulation and suspension techniques, have been shown to improve meat tenderness by alleviating rigor mortis and inducing an increase in sarcomere length. Electrical stimulation triggers an increase in calcium release, which activates proteolytic enzymes, including calpain, resulting in the breakdown of muscle fibers. In contrast, suspension methods, including pelvic suspension, utilize gravity to maintain muscle elasticity. Post-slaughter treatments, which include wet and dry aging, have varying effects on the tenderness and flavor of meat. Wet aging helps retain moisture and activate the meat-tenderizing enzymes, whereas dry aging enhances flavor through moisture evaporation and microbial activity. Several patented technologies, which include electrical stimulation combined with suspension methods, heat treatments, and microbial pre-treatment, have been developed to further improve the tenderness and flavor of meat during slaughter and aging. The application of these techniques promise significant enhancement in the quality and consumer appeal of cow meat.

Keywords cow meat, quality improvement, electrical stimulation, suspension method, aging

Introduction

Hanwoo (Korean native cattle) is a major source of meat in South Korea. To maintain the competitiveness of the industry, it is crucial to ensure that the quality of cow meat is suited to consumer preferences (Cho et al., 2024). Despite constituting a large part of Hanwoo cattle production, Hanwoo cow meat is often rated as low-quality grade (Park et al., 2002). In 2023, a total of 1,061,509 cattle were graded in Korea, of which 929,411 were Hanwoo (Korea Institute for Animal Products Quality Evaluation

[KAPE], 2023). Of these, Hanwoo cows constituted a substantial proportion of the total grading number (469,280 cattle, 50.5%; KAPE, 2023). Nevertheless, the proportion of Hanwoo cows graded as 1+ or above was only 59.3%, while that of steers was 91% (KAPE, 2023). The lower grading is mainly attributed to the high proportion of cows at older slaughter age, since 75.6% of Hanwoo cows were slaughtered at an age of 36 months or older (KAPE, 2023). As a result, the low quality grade of Hanwoo cow meat has resulted in economic losses for the producers and a decline in consumer satisfaction.

The meat from older cows of most breeds, including Hanwoo, tends to be of poor quality is the reduced marbling score (Park et al., 2002). Marbling, which refers to the distribution of intramuscular fat, is a critical factor in determining the flavor and tenderness of meat (Cheng et al., 2015). As cows age, energy metabolism shifts from fat accumulation to maintenance activities, leading to a decrease in intramuscular fat accumulation (Zhang and Guan, 2019). In addition, the activity of the fibroblasts involved in intramuscular fat formation diminishes with age, thereby reducing the development of new fat cells (Martins et al., 2015). Furthermore, older cows tend to accumulate fat in the subcutaneous (under-skin fat) and visceral areas (around organs), rather than in the muscles (Park et al., 2018). Hormonal changes also contribute to a decrease in the secretion of insulin and growth hormone with age, thus limiting intramuscular fat accumulation (Zhang and Guan, 2019). These factors lead to reduced marbling, and consequently, a lower meat quality grade in older cows.

In addition to reduced marbling, several other factors contribute to an increase in meat toughness (Chen et al., 2019). As cows age, changes in the muscle fiber composition lead to a higher proportion of type 1 muscle fibers, which are more rigid and result in tougher meat (Fu et al., 2019). The shortening of sarcomeres, the smallest structural units of muscle, occurs post-slaughter, and results in reduced muscle elasticity (Martins et al., 2015). There is an increase in collagen accumulation and cross-linking within the connective tissue with age, which makes the meat more resistant to breakdown during cooking (Phelps et al., 2017). Calpain enzymes, which are involved in the breakdown of muscle proteins, also show reduced activity with age. This limits the process involved in making meat tender (Ouali et al., 2013); consequently, the changes in the muscle fibers make beef tougher.

The present review aims to investigate various techniques for improving the quality characteristics of cow meat, specifically focusing on those applicable to multiparous cows and those slaughtered at older ages. It reviews several techniques that can be applied during or post-slaughter to improve meat quality.

Methods to Enhance Tenderness During the Slaughter Process

The slaughter process is a critical stage that determines the quality of meat. It involves several steps, including lairage, stunning, bleeding, suspension, skinning and removal, washing, splitting, and chilling (Webb and Agbeniga, 2020). During slaughter, the carcass undergoes rigor mortis, which keeps the muscles in a contracted state and increases meat toughness (Aalhus et al., 1999). Inadequate handling of rigor mortis leads to the shortening of muscle fibers and sarcomeres, which reduces meat tenderness (Aalhus et al., 1999). It can be avoided by implementing tenderness improvement techniques during the slaughter process. Previous research on improving beef tenderness during this process has focused on electrical stimulation and suspension methods.

Electrical stimulation method

Electrical stimulation alleviates rigor mortis, activates proteolytic enzymes, and reduces muscle fiber shortening (Alvarenga et al., 2024). Rigor mortis affects meat quality by preventing muscle relaxation after adenosine triphosphate (ATP) depletion

(Arp et al., 2021). Electrical stimulation after bleeding triggers the voltage-gated calcium channels in cells, resulting in the release of calcium ions from the sarcoplasmic reticulum within the muscle cells (Yang et al., 2019). The calcium ions bind to troponin and initiate muscle contraction. They also trigger the activation of calpain, a calcium-dependent proteolytic enzyme (Fallavena et al., 2020). This process plays a crucial role in alleviating rigor mortis and improving meat tenderness.

When the calcium ions released by electrical stimulation bind to troponin, tropomyosin moves to expose the binding sites on actin filaments; this allows the myosin heads to attach to actin molecules (Solaro and Rarick, 1998). During muscle contraction, the myosin heads hydrolyze ATP and interact with the actin filaments (Geeves, 1991). New ATP molecules bind to the myosin heads during muscle relaxation, allowing them to detach from actin (Geeves, 1991). The ATP-powered calcium pumps return calcium ions to the sarcoplasmic reticulum (Geeves, 1991), which results in its detachment from troponin. Tropomyosin once again covers the actin filament, resulting in the full relaxation of the muscle fiber (Geeves, 1991). Electrical stimulation accelerates calcium release, thereby shortening the time of muscle contraction and relaxation during rigor mortis.

The contraction and relaxation induced by electrical stimulation prevent the muscle fibers from becoming fixed in a shortened state, which helps in maintaining sarcomere length (Webb and Agbeniga, 2020). Calpain, a calcium-dependent proteolytic enzyme, is activated by an increase in the levels of calcium ions. It breaks down structural proteins, including desmin, troponin, nebulin, and titin, which provide structural support to muscle fibers (Aalhus et al., 1999). The breakdown of these structural proteins helps to alleviate rigor mortis (Aalhus et al., 1999). Therefore, electrical stimulation promotes the release of calcium ions, activates calpains, and breaks down structural proteins in the muscle, thereby effectively improving meat tenderness.

Various studies have reported the effects of electrical stimulation on improving beef tenderness (Table 1). Low-voltage electrical stimulation accelerates the initial pH drop, alleviates rigor mortis, and accelerates the breakdown of troponin T, leading to improved muscle tenderness (Arp et al., 2021; Webb and Agbeniga, 2020; Yang et al., 2019). Medium-voltage electrical stimulation (200–400 V) has also been found to improve tenderness, with 200 V being the most effective (Alvarenga et al., 2024). Studies have been conducted on electrical stimulation in combination with other treatments. Fallavena et al. (2020) observed improved meat tenderness on combining ultrasound with electrical stimulation. In contrast, Balan et al. (2019) found that electrical stimulation alone did not significantly affect tenderness, but did show improvements

Table 1. Research on electrical stimulation for improving beef tenderness during the slaughter process

Muscle/part name	Electrical stimulation	Results	Reference
Loin	ES1: 16 V, 20 V, 24 V, 28 V ES2: 25 V, 35 V, 45 V, 55 V	ES1: Shear force reduced by 10% ES2: Shear force reduced by 12% No significant difference between the treatments	Arp et al. (2021)
M. *longissimus lumborum* (LL), M. *biceps femoris* (BF)	45 V, 14.3 Hz, 7 ms, 60 s	LL: Shear force reduced by 19%, cooking loss increased by 5% BF: Shear force reduced by 11%, cooking loss increased by 2%	Yang et al. (2019)
M. *longissimus lumborum*	Different time treatments (30 s, 60 s)	30 s treatment reduced shear force by 7% compared to 60s	Webb and Agbeniga (2020)
M. *longissimus thoracis*	200 V, 300 V, 400 V	200V: Shear force reduced by 42%, cooking loss decreased by 2%	Alvarenga et al. (2024)
M. *longissimus lumborum*	13.3 Hz, 5.4 ms, 104 V, 30 s	Shear force reduced by 6%, cooking loss reduced by 21%	Balan et al. (2019)

when combined with high-temperature treatment. These studies demonstrate that electrical stimulation effectively improves beef tenderness by alleviating rigor mortis and promoting the activity of proteolytic enzymes.

Suspension methods

Suspension methods used during the slaughter process involve the suspension of the carcass in a specific position after bleeding, in order to improve muscle tenderness (Sørheim and Hildrum, 2002). It results in an increase in the sarcomere length due to gravity, leading to a decrease in the rigor mortis-induced shortening (England et al., 2012; Hwang, 2004). The main suspension methods used include the Achilles suspension and pelvic (hip bone) suspension (Moran et al., 2021; Pogorzelski et al., 2023). Achilles suspension uses the Achilles tendon to stretch the hindlimb (rear leg) muscles (M. *biceps femoris*, M. *semitendinosus,* M. *semimembranosus*; Pogorzelski et al., 2023). In contrast, pelvic suspension fixes the carcass at the ischium, which causes muscles, including M. *longissimus dorsi* and the abdominal muscles, to stretch under the influence of gravity. This method improves meat tenderness by maintaining or increasing sarcomere length (Eikelenboom et al., 1998; Park et al., 2008). The effect of the suspension methods on tenderness depends on the effect of gravity on each muscle (Table 2).

Pelvic suspension has been reported to have a positive effect on meat tenderness, especially on the muscles that constitute the loin (M. *longissimus dorsi,* M. *longissimus thoracis,* M. *longissimus lumborum*; Moran et al., 2021). Previous studies have reported that pelvic suspension increases sarcomere length and decreases shear force, thereby improving tenderness (Eikelenboom et al., 1998). Eikelenboom et al. (1998) reported that pelvic suspension increased the sarcomere length of M. *longissimus thoracis et lumborum* from 1.86 μm to 2.25 μm (a 21% increase) and decreased shear force from 67.7 N to 53.3 N. Similarly, England et al. (2012) observed an increase in sarcomere length for M. *longissimus dorsi* from 1.82 μm to 2.43 μm, while shear force reduced from 62.8 N to 51.2 N. Hou et al. (2014) and Hwang (2004) also reported similar improvements in sarcomere length and shear force reduction across the loin muscles. Jaspal et al. (2021) and Nian (2017) reported positive effects of pelvic suspension on M. *longissimus thoracis* and M. *longissimus lumborum*, which confirmed the effectiveness of this method in reducing shear force and improving tenderness. Notably, Nian (2017) found that pelvic suspension achieved the same levels of tenderness as 7-day aged Achilles suspension by day 3 of aging. Overall, pelvic suspension has been consistently shown to outperform Achilles suspension in improving tenderness in the loin muscles.

Pelvic suspensions have also been shown to improve the quality of leg muscles, including those of M. *gluteus medius,* M. *biceps femoris,* M. *semitendinosus,* and M. *semimembranos*. Moran et al. (2021) reported that pelvic suspension increased the sarcomere length of M. *gluteus medius* from 1.92 μm to 2.35 μm, while reducing shear force from 39.5 N to 24.6 N, which resulted in a significant improvement in meat tenderness. Similarly, Nian (2017) found that in M. *gluteus medius*, pelvic suspension decreased shear force from 42.54 N to 40.18 N after 3 days post-mortem, and from 40.73 N to 36.82 N after 7 days, with the difference at 7 days being statistically significant ($p<0.05$). Ahnström et al. (2012) observed that, in cull cows, pelvic suspension increased sarcomere length in M. *gluteus medius* from 1.81 μm to 2.57 μm, while shear force decreased slightly from 40.0 N to 39.4 N, which further confirmed its positive impact on muscle tenderness. For M. *biceps femoris*, Baxter et al. (1972) reported that pelvic suspension increased the sarcomere length from 1.79 μm to 2.40 μm, while significantly reducing shear force from 7.8 kg to 4.9 kg, with a significant improvement in tenderness. Pogorzelski et al. (2023) also found that pelvic suspension increased tenderness by 12%, with the tenderness score rising from 35.70 to 41.96; the findings highlighting the effectiveness of pelvic suspension in improving muscle quality across various leg muscles. For M. *semitendinosus*, pelvic suspension showed mixed results. England et al. (2012) reported that pelvic suspension increased

Table 2. Research on suspension method for improving beef tenderness during the slaughter process

Muscle/part name	Suspension method	Results	Reference
M. *longissimus thoracis et lumborum*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 21%, shear force decreased by 13%, cooking loss decrease by 2%	Eikelenboom et al. (1998)
M. *longissimus dorsi*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 33.5%, shear force decreased by 17%,	England et al. (2012)
M. *longissimus dorsi*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 24%, shear force decreased by 19%, cooking loss decrease by 29%	Hou et al. (2014)
M. *longissimus dorsi*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 16%, shear force decreased by 12%, cooking loss decrease by 6%	Hwang (2004)
M. *longissimus thoracis*	Achilles/Pelvic	Pelvic suspension: shear force decreased by 13%	Nian (2017)
M. *longissimus lumborum*	Achilles/Pelvic	Pelvic suspension: shear force decreased by 19%	Jaspal et al. (2021)
M. *longissimus lumborum*	Achilles/Pelvic	Pelvic suspension: shear force decreased by 15%	Nian (2017)
M. *gluteus medius*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 12%, shear force decreased by 16%	Moran et al. (2021)
M. *gluteus medius*	Achilles/Pelvic	Pelvic suspension: shear force decreased by 9%	Nian (2017)
M. *gluteus medius*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 50%, shear force decreased by 23%	Ahnström et al. (2012)
M. *biceps femoris*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 23%, shear force decreased by 21%	Baxter et al. (1972)
M. *biceps femoris*	Achilles/Pelvic	Pelvic suspension: tenderness increased by 12%, juiciness increased by 10%	Pogorzelski et al. (2023)
M. *semitendinosus*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 26%	England et al. (2012)
M. *semitendinosus*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 2%, shear force decreased by 1%	Moran et al. (2021)
M. *semitendinosus*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 12%	Nian (2017)
M. *semitendinosus*	Achilles/Pelvic	Pelvic suspension: tenderness increased by 5%, juiciness increased by 17%	Pogorzelski et al. (2023)
M. *semimembranosus*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 47%, shear force decreased by 11%, cooking loss decrease by 6%	Eikelenboom et al. (1998)
M. *semimembranosus*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 13%, shear force decreased by 11%, cooking loss decrease by 4%	Hwang (2004)
M. *semimembranosus*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 9%, shear force decreased by 10%, cooking loss decrease by 5%	Park et al. (2008)
M. *semimembranosus*	Achilles/Pelvic	Pelvic suspension: shear force decreased by 21%, cooking loss decrease by 4%	Ahnström et al. (2006)
M. *semimembranosus*	Achilles/Pelvic	Pelvic suspension: Sarcomere length increased by 44%, shear force decreased by 22%	Ahnström et al. (2012)

sarcomere length from 2.36 μm to 2.97 μm, thus demonstrating its ability to stretch the muscle and improve tenderness. Similarly, Nian (2017) found that pelvic suspension increased sarcomere length in M. *semitendinosus* from 1.73 μm to 2.46 μm, which supported its role in enhancing meat quality. However, Moran et al. (2021) found that pelvic suspension had no significant effect on sarcomere length or shear force in M. *semitendinosus*, with both pelvic and traditional suspensions resulting in sarcomere lengths of 1.69 μm and shear force of 36.9 N. Similarly, Pogorzelski et al. (2023) reported no significant difference in the tenderness or juiciness of M. *semitendinosus* between pelvic and Achilles suspensions. Pelvic suspensions have also been shown to exert notable effects on M. *semimembranosus*. Eikelenboom et al. (1998) reported that pelvic suspension increased the sarcomere length of M. *semimembranosus* from 1.78 μm to 2.62 μm, a 47% increase when compared to Achilles tendon suspension. The pelvic suspension reduced the shear force from 160 to 140 N/cm² and cooking loss from 35.5% to 33.4%. Hwang (2004) also reported that pelvic suspension increased sarcomere length from 1.8 μm to 2.9 μm and reduced cooking loss from 25.4% to 23.9%. In a more recent study, Parket al. (2008) found similar results, with an increase in the sarcomere length to 2.84 μm and a slight reduction in shear force from 39.9 N to 38.8 N. Ahnström et al. (2006) further confirmed these findings by demonstrating a 21% reduction in shear force from 67.7 N to 53.3 N, and a decrease in cooking loss from 28.8% to 27.6%. In their study, Ahnström et al. (2012) observed similar effects in cull cows, with sarcomere length increasing to 2.84 μm and shear force reduced from 48.8 N to 36.1 N, which further demonstrated the effectiveness of pelvic suspension in improving meat tenderness in mature cows.

In conclusion, pelvic suspension was found to be more effective than Achilles suspension in improving the tenderness in loin muscles (M. *Longissimus dorsi*, M. *Longissimus thoracis*, M. *Longissimus lumborum*) by increasing sarcomere length and reducing shear force. These results are consistent across multiple studies. However, the effects of pelvic suspension on the leg muscles vary, depending on the specific muscle type. Although M. *gluteus medius* and M. *biceps femoris* showed notable improvements in tenderness and sarcomere length, M. *semitendinosus* has yielded mixed results, with some studies reporting no significant differences in tenderness or shear forces. These findings suggest that the effectiveness of suspension methods in improving tenderness may differ based on the characteristics of individual muscles.

Methods to Enhance Tenderness Post-Slaughter

Post-slaughter tenderness can be improved using aging methods, which are generally categorized as wet or dry aging (Ali et al., 2021). Wet aging involves vacuum-sealing the meat and storing it in a refrigerated environment, where natural enzymes break down proteins and improve meat tenderness (Ali et al., 2021). This method minimizes moisture loss and keeps meat moist (Kim et al., 2019). In contrast, dry aging involves exposing meat to air, which causes moisture to evaporate while natural and microbial enzymes break down the proteins present in meat (Bulgaru et al., 2022). This process concentrates flavors and gives the meat a richer taste and texture; however, moisture loss can lead to a reduction in weight (Utama et al., 2020). The details of these two aging methods are summarized in Table 3.

Wet aging method

Wet aging improves meat texture by activating natural proteolytic enzymes, including calpain, which are involved in the breakdown of proteins in muscle fibers and connective tissues (Dashmaa et al., 2013). This process helps soften the texture of meat. In particular, it promotes the breakdown of collagen, weakens connective tissue, and improves tenderness (Utama et al., 2020). Additionally, since the meat is aged in vacuum-sealed packaging, moisture loss is minimum. This helps keep the meat moist and tender in texture (Kim et al., 2022). An increase in sarcomere length and a reduction in shear force have been observed because of wet aging in the *longissimus* muscle group and associated loin cuts, as well as in the hindquarter muscles and cuts (Ali et al., 2021; Cho et al., 2016; Fu et al., 2019; Jaspal et al., 2021; Kim et al., 2019; Kim et al., 2022; Moczkowska et al., 2017; Shi et al., 2020). In the M. *longissimus thoracis*, wet aging reduced the shear force value from 5.29 kg to 2.23 kg (Ali et al., 2021). For M. *longissimus lumborum*, Shi et al. (2020) reported that 14 days of wet aging reduced the shear force value from 5.29 kg to 2.23 kg. Similarly, Moczkowska et al. (2017) found that 14 days of wet aging decreased the shear force

Table 3. Characteristics of techniques used after slaughter for meat tenderness improvement

Muscle/part name	Aging	Results	Reference
M. *longissimus thoracis*	Wet (4°C) 10 day	Shear force decreased by 58% Cooking loss decrease by 20%	Ali et al. (2021)
M. *longissimus lumborum*	Wet (2°C) 14 day	Shear force decreased by 58% Cooking loss decrease by 8%	Shi et al. (2020)
M. *longissimus lumborum*	Wet (1°C) 14 day	Shear force decreased by 23% Cooking loss decrease by 4%	Moczkowska et al. (2017)
Sirloin	Wet (2°C) 28 day	Shear force decreased by 42% Cooking loss decrease by 3%	Kim et al. (2019)
Sirloin	Wet (4°C) 60 day	Shear force decreased by 51%	Kim et al. (2022)
Loin	Wet (4°C) 21 day	Sarcomere length increased by 13% Shear force decreased by 48% Cooking loss decrease by 6%	Cho et al. (2016)
Striploin	Wet (4°C) 21 day	Sarcomere length increased by 16% Shear force decreased by 49% Cooking loss decrease by 3%	Cho et al. (2016)
M. *biceps femoris*	Wet (4°C) 10 day	Shear force decreased by 15% Cooking loss decrease by 4%	Ali et al. (2021)
M. *biceps femoris*	Wet (2°C) 14 day	Shear force decreased by 19% Cooking loss decrease by 4%	Moczkowska et al. (2017)
Bottom round	Wet (4°C) 21 day	Sarcomere length increased by 1% Shear force decreased by 42% Cooking loss decrease by 3%	Cho et al. (2016)
Rump	Wet (2°C) 28 day	Shear force decreased by 32% Cooking loss decrease by 2%	Kim et al. (2019)
M. *longissimus lumborum*	Dry 28 day	Shear force decreased by 25% Cooking loss decrease by 14%	Jose et al. (2020)
Sirloin	Dry 28 day	Shear force decreased by 41% Cooking loss decrease by 28%	Kim et al. (2019)
Sirloin	Dry 60 day	Shear force decreased by 10%	Kim et al. (2022)
Ribeye	Dry 21 day	Hardness decreased by 79%	Bulgaru et al. (2022)
Butt	Dry 28 day	Shear force decreased by 34% Cooking loss decrease by 16%	Kim et al. (2019)
Rump	Dry 28 day	Shear force decreased by 34% Cooking loss decrease by 18%	Kim et al. (2019)

from 38.61 N to 29.55 N. Kim et al. (2019) reported that, in sirloin, wet aging for 28 days reduced the shear force from 63.26 N to 36.48 N. Kim et al. (2022) reported that wet aging for 60 days reduced the shear force from 6.38 kg to 3.10 kg. In loin and striploin, wet aging for 21 days reduced the shear force from 5.36 kg to 2.79 kg and from 5.15 kg to 2.62 kg, respectively. It also increased the sarcomere length from 2.99 μm to 3.37 μm in the loin, and from 3.02 μm to 3.51 μm in the striploin, respectively (Cho et al., 2016). In the M. *biceps femoris*, the shear force value decreased from 4.92 kg (before aging) to 4.17 kg after 10 days of wet aging (Ali et al., 2021). Similarly, Moczkowska et al. (2017) reported that the shear force of the *biceps femoris* muscle decreased from 64.2 N to 48.5 N after 14 days of wet aging, leading to improved tenderness. In addition, Cho et al. (2016) found that the bottom round muscle experienced a reduction in shear force from 6.14 kg to 3.55 kg after 21 days of wet aging, along with a slight increase in sarcomere length from 2.33 μm to 2.35 μm. This finding further

supports the tenderizing effects of wet aging across different muscle cuts. Kim et al. (2019) also demonstrated that wet aging for 28 days significantly improved the tenderness of rump muscles, reducing the shear force from 70.58 N to 48.01 N. These consistent reductions in shear force across various muscle cuts further emphasized the effectiveness of wet aging in enhancing meat tenderness by promoting proteolytic activity and increasing muscle fiber extension.

Dry aging method

Dry aging plays a crucial role in improving both the tenderness and flavor of meat (Bulgaru et al., 2022). Proteolytic enzymes are activated during the aging process, which breakdown proteins in muscle fibers and connective tissues and soften the meat texture (Utama et al., 2020). In addition to the activity of the enzymes, dry aging also involves the microorganisms on the surface of the meat. The latter are also involved in the breakdown of proteins and fats, thereby contributing to the development of unique flavors (Kim et al., 2022). Moisture evaporates when meat is exposed to air, resulting in the concentration of proteins and connective tissues inside the meat and enhancing the depth of flavor (Dashmaa et al., 2013). However, the drawbacks of dry aging are that this process leads to moisture loss and weight reduction (Bulgaru et al., 2022). Nevertheless, dry aging is highly effective in improving both the tenderness and flavor (Utama et al., 2020). In M. *longissimus lumborum*, the shear force decreased from 43.15 N to 34.22 N after 28 days of dry aging, demonstrating a similar improvement in tenderness (Jose et al., 2020). Kim et al. (2019) found that the shear force in sirloin decreased from 63.26 N to 36.48 N after 28 days of dry aging, further confirming the effectiveness of dry aging in improving tenderness. Similarly, Kim et al. (2022) reported that the shear force in sirloins decreased from 6.36 kg to 3.10 kg after 60 days of dry aging, showing a significant enhancement in tenderness. Additionally, Bulgaru et al. (2022) observed that the hardness of ribeye decreased significantly from 1,592.55 g to 331.58 g after 21 days of dry aging, further demonstrating the tenderizing effects of dry aging on various cuts of meat. Kim et al. (2019) reported significant reductions in shear force in the butt and rump muscles after 28 days of dry aging, with reductions from 70.81 kg to 38.79 kg in the butt, and from 70.58 kg to 48.01 kg in the rump, which confirmed the consistent tenderizing effects across different cuts. In addition to these textural improvements, dry aging also leads to a notable flavor development. Ba et al. (2013) reported an increase in compounds such as hexanal, 2-methylpyrazine, and methanethiol during dry aging, with hexanal providing a fresh, fatty-green aroma, 2-methylpyrazine contributing to Maillard reaction flavors, while methanethiol resulted in onion and garlic-like aromas. Dashmaa et al. (2013) observed an increase in free amino acids during dry aging, including glutamic acid and alanine, which resulted in the umami and sweet flavors.

Patented Technologies for Enhancing Tenderness

Patented technologies for improving beef quality have been applied in different ways during slaughter and aging processes, in order to enhance meat tenderness (Table 4). During slaughter, stretching, electrical stimulation, and suspension technologies are primarily used to alleviate rigor mortis and promote protein degradation, which softens meat and improves its quality (Bell et al., 2008; Fisher et al., 1999; Williams, 1957). Stouffer et al. (1969) patented a method for improving meat tenderness by stretching the muscle fibers after slaughter. Howard et al. (2001) patented a machine designed to stretch muscle fibers mechanically. Pelvic suspensions have been shown to improve beef tenderness. The pelvic suspension method was patented by Gardner et al. (2014) and was confirmed to reduce the shear force in the *gluteus medius*, *biceps femoris*, and knuckle muscles. Electrical stimulation is applied to the muscles of cattle immediately after slaughter. It induces muscle contraction

Table 4. Summary of patented technologies for enhancing meat tenderness

Muscle/part name	Characteristics	Results	Reference
M. *longissimus*	Pre-rigor vertebral separation	Improved tenderness by stretching muscle fibers	Stouffer et al. (1969)
Beef	Pre-rigor vertebral separation	Mechanical device used for stretching muscle fibers	Howard et al. (2001)
M. *gluteus medius*	Pelvic suspension	Shear force reduction by 20%	Gardner et al. (2014)
M. *biceps femoris*	Pelvic suspension	Shear force reduction by 20%	Gardner et al. (2014)
Kuckle muscle	Pelvic suspension	Shear force reduction by 19%	Gardner et al. (2014)
Beef	Aging after electrical stimulation treatment	Aging period shortened by 91%	Harsham and Deatherage (1951)
M. *gluteus medius*	Combined treatment of pelvic suspension after electrical stimulation	Shear force reduction by 33%	Gardner et al. (2014)
M. *biceps femoris*	Combined treatment of pelvic suspension after electrical stimulation	Shear force reduction by 37%	Gardner et al. (2014)
Kuckle muscle	Combined treatment of pelvic suspension after electrical stimulation	Shear force reduction by 34%	Gardner et al. (2014)
Beef	Starter culture with temperature and humidity-controlled aging	Aging period shortened by 67%	Williams (1957)
Chuck	Flavor-enhancing microbial inoculation dry aging	Shear force reduced by 24%	Jo et al. (2020)
Fore shank	Flavor-enhancing microbial inoculation dry aging	Shear force reduced by 29%	Jo et al. (2020)
Top around	Flavor-enhancing microbial inoculation dry aging	Shear force reduced by 25%	Jo et al. (2020)
Brisket	Flavor-enhancing microbial inoculation dry aging	Shear force reduced by 29%	Jo et al. (2020)
Sirloin	Temperature and humidity-controlled dry aging	Shear force reduced by 15%	Jo et al. (2019)
Knuckle	Temperature and humidity-controlled dry aging	Shear force reduced by 30%	Jo et al. (2019)
Brisket	Temperature and humidity-controlled dry aging	Shear force reduced by 16%	Jo et al. (2019)
Sirloin	Low-temperature and high-temperature combined drying and aging	Taurine increased by 15%	Yu (2013)
Sirloin	High-temperature aging after thermal processing and electron beam irradiation	Shear force reduced by 53%	Nam and Jo (2015)
Striploin	High-temperature aging after ultraviolet treatment	Shear force reduced by 36%	Byun and Kim (2020)
Beef	High-pressure air and low-temperature combined wet aging	Effective aging	Jung et al. (2016)
Beef	Wet aging combined with ultrasonic treatment	Glutamic acid increased by 35%	Kim (2020)
Beef	Combined dry and wet aging	Sensory evaluation preference increased by 13%	Choi (2020)
Beef	Enzyme injection through absorbent pad, combined wet and dry aging	Sensory evaluation showed enhanced elastic texture	Kim et al. (2022)

and relaxation, which helps to reduce rigor mortis and improve tenderness (Bell et al., 2008). Harsham and Deatherage (1951) patented a technology to reduce the aging time through electrical stimulation during the slaughter process. The combined treatment of electrical stimulation followed by pelvic suspension was also patented by Gardner et al. (2014) and was found to reduce shear force in the M. *gluteus medius*, M. *biceps femoris*, and knuckle muscles.

Similarly, various techniques involving temperature, humidity, and microbial treatments are employed during the aging process to further enhance the flavor and texture of meat (Jo et al., 2019; Jo et al., 2020; Yu, 2013). Williams (1957) patented a method to shorten the aging period by using a temperature between 45°F and 60°F, a relative humidity of over 80%, and inoculation with *Thamnidium* mold. Jo et al. (2019) patented a method to improve the tenderness of chuck, foreshank, top round, and brisket meat through dry aging, accompanies by the inoculation of *Debaryomyces hansenii* and *Penicillium camembertii*. Jo et al. (2019) patented a method to enhance the tenderness of sirloin, knuckle, and brisket through dry aging under controlled temperature and humidity (2℃, 65%, 20 days; 2℃, 75%, 20 days; 4℃, 85%, 50 days). Yu (2013) patented a method to increase taurine levels in sirloin through dry aging at low temperatures (1℃–5℃), followed by higher temperatures (10℃–20℃). Several other patents describe the use of electron beam irradiation or ultraviolet treatment to remove surface microorganisms and perform high-temperature dry aging (Byun and Kim, 2020; Nam and Jo, 2015). Nam and Jo (2015) patented a method to improve the tenderness of sirloin by irradiating it with 2 kGy of electron beam, followed by dry aging at 25℃. Byun and Kim (2020) patented a method to increase the tenderness of striploins by dry aging after ultraviolet irradiation (200–2,000 mWs/cm^2). Some wet-aging-related patents are a combination of high-pressure air and ultrasonic treatments. Jung et al. (2016) patented a method to achieve effective aging through wet aging at low temperatures (0℃), in combination with high-pressure air (1.95 MPa). Kim (2020) patented a method to increase the level of glutamic acid in beef by combining ultrasonic treatment (0.2–3 MHz) with wet aging (–1.7℃ to 0.5℃). A few other patents include methods involving a combination of dry and wet aging. Choi (2020) patented a method to improve sensory preference through a combination of dry aging (–1.5℃ to 3℃ for 1 d) and vacuum-packaged wet aging for 3 days. A tenderizer (15% gum arabic, 45% maltodextrin, 40% arrowroot) was applied at 1.5%, and the combination of wet and dry aging was found to improve beef elasticity.

Hence, various patented technologies have been developed for both slaughter and post-slaughter processes to improve the tenderness and flavor of beef.

Summary

A comparison of various slaughter and post-slaughter methods for improving the tenderness and quality of beef offers significant benefits. Electrical stimulation during slaughter accelerates ATP depletion and promotes calcium release, which activates proteolytic enzymes, including calpain. This results in the breakdown of structural proteins in muscles, which enhances meat tenderness. Suspension methods, which includes pelvic suspension, involves the application of physical forces to stretch muscles, increase sarcomere length, and improve tenderness. Post-slaughter technologies, including wet and dry aging, enhance the quality of meat in distinct ways. Wet-aging maintains tenderness by activating proteolytic enzymes in a vacuum-sealed environment, which leads to a breakdown of muscle fibers and connective tissues while minimizing moisture loss. On the other hand, dry aging not only improves tenderness but also enhances flavor through enzymatic and microbial activity, resulting in the development of richer tastes as moisture evaporates. Although dry aging results in some weight loss, the improvement in flavor makes it a highly desirable method for specific meat cuts. Patented methods for improving meat tenderness include electrical stimulation, suspension techniques, heat treatment, and various aging methods. These findings demonstrate that the application of appropriate slaughter and post-slaughter technologies can significantly improve beef quality. However, while these techniques have been extensively studied for general beef production, there is limited research specifically applying them to multiparous cow meat. Therefore, future research should prioritize exploring these technologies to address the unique characteristics of multiparous cow meat and improve its quality.

Conflicts of Interest

The authors declare no potential conflicts of interest.

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Author Contributions

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Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

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