Effects of Dietary Antioxidants on Muscle Tenderness and Mechanisms of Action: Postprint

Authors: Xu Shaoting, Xu Chenchen, Luo Hailing

Date: 2017-10-11T00:00:00+00:00

Abstract

Tenderness constitutes one of the crucial sensory indicators of muscle quality, determining both its nutritional and eating qualities. During intensive animal production, the inevitable oxidative stress generated exerts substantial adverse effects on muscle quality; therefore, exploring effective measures to ameliorate the impact of oxidative stress on muscle tenderness is of paramount importance. By synthesizing the current research status of meat tenderness both domestically and internationally, this review primarily elaborates on the effects of oxidative stress and antioxidants on muscle tenderness and their underlying mechanisms, aiming to provide a reference for the efficient and rational utilization of antioxidants to improve muscle tenderness.

Full Text

Preamble

Effects and Mechanisms of Dietary Antioxidants on Meat Tenderness

XU Shaoting, XU Chenchen, LUO Hailing*
(State Key Laboratory of Animal Nutrition, College of Animal Science and Technology, China Agricultural University, Beijing 100193, China)

Abstract: Tenderness is a crucial sensory indicator of meat quality that determines both nutritional and eating quality. However, oxidative stress, which inevitably occurs during intensive animal production, exerts substantial adverse effects on meat quality. Therefore, exploring effective measures to mitigate the impact of oxidative stress on meat tenderness is essential. Based on current research on meat tenderness both domestically and internationally, this review elaborates on the effects of oxidative stress and antioxidants on meat tenderness and their underlying mechanisms, aiming to provide a reference for the efficient and rational use of antioxidants to improve meat tenderness.

Keywords: meat quality; tenderness; diet; antioxidants
CLC number: S811

*Corresponding author, professor, E-mail: luohailing@cau.edu.cn

Since China' s reform and opening up, the livestock industry has developed rapidly, with national meat production reaching 86.25 million tons in 2015 according to the China Statistical Yearbook (2016). As global economic levels rise and consumer preferences evolve, demands for meat products have increased accordingly, making the improvement of meat tenderness a long-standing research focus among scientists. Tenderness refers to the shear force required to cut muscle with a knife or the overall perception of hardness when chewing cooked meat, reflecting its softness and ease of mastication. It is one of the most important indicators for evaluating meat quality, as well as the least stable and most susceptible to interference [1-2]. Tenderness is typically assessed through sensory evaluation or instrumental methods. During production, processing, storage, and transportation, oxidative stress induced by factors such as intensive farming, malnutrition, long-distance transport, extreme environments, and frozen storage increases peroxidation reactions, making muscle highly susceptible to oxidative deterioration, reducing tenderness and color stability, and shortening shelf life [3]. Therefore, adding exogenous antioxidants to feed to inhibit muscle oxidation has become an effective approach for extending shelf life and improving meat quality. Current research on dietary antioxidants has primarily concentrated on their effects on animal antioxidant capacity, growth performance, and general meat quality indicators, while studies specifically addressing their effects on meat tenderness and underlying mechanisms remain relatively limited. Therefore, elucidating and summarizing the mechanisms by which antioxidants affect meat tenderness is of great significance for their rational and efficient utilization.

1. Effects of Oxidative Stress on Meat Tenderness

During animal production, various factors including farming conditions, preslaughter environment, and transport stress can cause excessive free radical concentrations in the body, leading to oxidative stress that adversely affects animal health, production performance, and product quality [4]. Oxidative stress can cause muscle oxidative deterioration, manifested as discoloration, off-flavors, and even formation of toxic substances, resulting in reduced shelf life and compromised nutritional quality and tenderness [5]. High levels of free radicals reduce muscle sensory quality and tenderness, causing loss of protein function and depletion of essential amino acids such as phenylalanine and tryptophan, making it crucial to understand free radical activity in meat [6-8].

A small portion (2-5%) of oxygen consumed during metabolic reactions is converted into reactive oxygen species [9], which play key regulatory roles in homeostasis by interacting with proteins, fatty acids, and nucleic acids. However, excessive free radicals in muscle readily react with the abundant polyunsatu-

rated fatty acids in biological membrane structures, initiating chain reactions that generate a series of lipid oxidation products. Reactive oxygen species, reactive nitrogen species, and lipid oxidation products can all induce oxidative modification of proteins or enzymes, altering their structure and properties and consequently changing enzyme activities, thereby modifying meat tenderness [10-11].

Yang et al. [12] reported that the tenderness of longissimus dorsi muscle in fattening pigs under high temperature stress (30°C) was significantly lower than that of the control group (22°C). Yan et al. [13] found that electric shock driving stress significantly reduced the tenderness of longissimus dorsi muscle in Northeast Min pigs post-slaughter, affecting meat quality. Animals experience relatively low oxidative stress and high antioxidant capacity during the live state, whereas post-slaughter, particularly during the conversion of muscle to meat, there is high oxidative stress and relatively low antioxidant capacity to reverse oxidation [14]. This difference between the two states underscores the importance of oxidative stress for meat quality. Due to the complex and diverse factors causing oxidative stress, different oxidative stress conditions exert varying degrees of impact on muscle tenderness, and thus the mechanisms and effects of different antioxidants also differ.

2. Mechanisms of Action of Antioxidants on Meat Tenderness

Muscle tenderness is fundamentally determined by the content, physicochemical properties, and internal biochemical state of muscle fibers, connective tissue, and intramuscular fat. All factors affecting muscle structure and internal state can indirectly influence tenderness, including breed and genetics, sex, age, feed nutrition, management practices, slaughter processing, and post-slaughter aging. The primary cause of tenderness variation is the degradation of myofibrillar proteins such as desmin, titin, and nebulin, which involves multiple protease systems, with the calpain-calpastatin system being the most important [15-16].

Dietary antioxidants improve meat tenderness by enhancing the antioxidant capacity of animals and post-slaughter muscle, inhibiting oxidation of proteins, enzymes, and lipids by reactive oxygen and nitrogen species, and protecting the structural and functional integrity of muscle proteins and enzymes [17]. Pan [18] conducted in vitro experiments inducing myofibrillar protein oxidation, demonstrating that oxidation during storage increased carbonyl content, cross-linking degree, and particle size of myofibrillar proteins while reducing total sulfhydryl content, with myosin being most susceptible to oxidative cross-linking. The study also showed that adding compound antioxidants during meat storage could block protein oxidation pathways and improve tenderness. Li et al. [19] found that dietary vitamin E supplementation significantly improved pork tenderness, while ultrastructural analysis of muscle fibers revealed that vitamin E significantly increased sarcomere length and I-band length while decreasing myofibril diameter, all of which are closely related to meat tenderness. Zhang et

al. [20] reported that licorice extract could inhibit free radical attack on calpain, increasing its activity and promoting muscle protein degradation, suggesting that antioxidants affect meat tenderness by enhancing calpain activity during aging.

3. Effects of Dietary Antioxidant Supplementation on Meat Tenderness

Adding exogenous antioxidants to feed or muscle can directly or indirectly scavenge free radicals in the body or muscle, improving antioxidant performance. Exogenous antioxidants are diverse, including natural antioxidants such as vitamin E, vitamin C, and α-lipoic acid; plant extracts such as isoflavones, tea polyphenols, lycopene, and spice extracts; and other antioxidant compounds.

3.1 Vitamins

Numerous studies have shown that adding certain vitamins to animal feed can improve antioxidant performance. Vitamin E, a tocopherol compound, possesses multiple biological functions including antioxidant activity, growth promotion, and reproductive enhancement. As an important component of lipid membranes, vitamin E protects membrane structure and function by scavenging free radicals, thereby preventing cytoplasmic leakage and increasing meat tenderness [21]. Vitamin C can scavenge free radicals by donating electrons or restore the antioxidant function of vitamin E, exhibiting synergistic effects. However, many studies have found that vitamin C and E can act as pro-oxidants in the presence of transition metal ions or at high doses, indicating that antioxidants may exert pro-oxidant effects under certain conditions.

Wang [22] demonstrated that different doses of vitamin E and vitamin C affected tenderness differently across muscle types. Vitamin C supplementation at 150 and 300 mg/kg significantly improved leg muscle tenderness but had no significant effect on breast muscle tenderness, whereas dietary vitamin E at 100 mg/kg significantly improved breast muscle tenderness. The study also confirmed that individual supplementation of vitamin C or vitamin E could significantly improve antioxidant performance in broilers and muscle during cold storage. Research indicates that vitamin E must accumulate to a certain concentration in animal tissues to affect meat quality, with tissue concentrations influenced by dietary supplementation level and duration [23-24]. These findings suggest that different doses of vitamin E and vitamin C may have differential effects on muscle quality across animal body parts, and that excessive or insufficient supplementation may fail to improve certain meat quality indicators.

3.2 Plant Extracts

Many studies have found that numerous plants and their extracts possess strong antioxidant functions, primarily related to their phenolic and aldehyde contents,

such as lycopene, tea polyphenols, honeysuckle extract, resveratrol, guava powder, mulberry leaves, and oregano. However, most current research has focused on effects on animal antioxidant capacity and growth performance, with few reports on their effects on meat tenderness and mechanisms. Lycopene, a carotenoid found mainly in ripe red fruits such as tomatoes and guavas, exhibits strong antioxidant properties [25]. Jiang [26] showed that lycopene has good antioxidant function both in vivo and in vitro, and that dietary supplementation improved lamb tenderness, though not significantly. Tea polyphenols, bioactive substances in tea, primarily include catechins, flavonols, and anthocyanins [27]. According to Ministry of Agriculture Announcement No. 2045, tea polyphenols are approved antioxidants for use in livestock feed. Chao et al. [28] investigated the effects of tea polyphenols on antioxidant capacity and meat quality in fattening pigs, finding that 0.04% dietary supplementation had no significant effect on tenderness despite significantly improving antioxidant capacity. Yao et al. [29] found that 0.009% and 0.013% dietary tea polyphenol supplementation significantly improved pork antioxidant capacity and tended to improve tenderness, though not significantly. Dietary supplementation with honeysuckle extract, resveratrol, guava powder, and mulberry leaves has significantly improved muscle tenderness [30-33]. However, some studies found that oregano essential oil had no significant effect on lamb or pork tenderness [34-35]. These discrepancies may be related to antioxidant type, dosage, experimental duration, and animal factors.

3.3 Other Antioxidants

Many single antioxidants or antioxidant-containing products have demonstrated strong antioxidant functions in vivo or in vitro, such as α-lipoic acid, microbial additives, and dihydropyridine. However, numerous studies have found that these products have widely varying effects on meat tenderness. Guo [36] demonstrated that α-lipoic acid significantly improved antioxidant capacity and meat tenderness in broilers. Zhang et al. [37] evaluated the effects of feeding Lactobacillus solution on pork quality and antioxidant capacity, showing that it significantly improved both tenderness and antioxidant performance. Bian et al. [38] found that dietary dihydropyridine supplementation increased pork tenderness, though not significantly. Li et al. [39] showed that feeding rice bran significantly reduced pork tenderness, while supplementation with additives containing glutathione, dihydropyridine, and zinc sulfate significantly improved tenderness. Different antioxidants may have multiple biological functions and varied mechanisms of action on muscle, warranting further investigation into their effects on meat tenderness.

Feed antioxidants primarily exert their effects by directly or indirectly scavenging or reducing excess free radicals in the animal body, thereby maintaining dynamic balance of free radical content, improving tissue and muscle antioxidant capacity, and inhibiting lipid oxidation, protein oxidation, and enzyme activity decline in muscle, ultimately improving tenderness. The application of

antioxidants as feed additives in livestock production has attracted considerable research attention, with numerous published studies. However, most research has focused on exploring new antioxidants and their effects on animal health, production performance, and general meat quality indicators, while systematic studies on their specific effects on meat tenderness and underlying mechanisms are lacking. Future research should deeply explore the mechanisms by which antioxidants affect meat tenderness while ensuring animal health and safety, providing theoretical basis for the rational and effective use of antioxidants to reduce adverse effects of stress on meat quality.

References

[1] ZHANG WL. Determination of pork texture and flavor[J]. Swine Production, 2002(4):33-35.
[2] HUANG HB, XU XL. Meat color and tenderness[J]. Meat Research, 2003(3):12-14.
[3] ZHONG R Z,ZHOU D W,TAN C Y,et al.Effect of tea catechins on regulation of antioxidant enzyme expression in H2O2-induced skeletal muscle cells of goat in vitro[J].Journal of agricultural and food chemistry,2011,59(20):11338-11343.
[4] JIANG HQ, LUO HL, QU YH. Biological characteristics of lycopene and its application prospects in animal production[C]//Proceedings of the 2014 National Symposium on Sheep Production and Academic Research. Liaocheng: Sheep Science Branch of Chinese Association of Animal Science and Veterinary Medicine, 2014:29-31.
[5] CONTINI C,ÁLVAREZ R,O' SULLIVANA M,et al.Effect of an active packaging with citrus extract on lipid oxidation and sensory quality of cooked turkey meat[J].Meat Science,2014,96(3):1171-1176.
[6] EL-AAL H A H M A.Lipid peroxidation end-products as a key of oxidative stress:effect of antioxidant on their production and transfer of radicals[M]//CATALA A.Lipid Peroxidation.[S.l.]:INTECH Open Access Publisher,2012.
[7] LUND M N,HEINONEN M,BARON C P,et al.Protein oxidation in muscle foods:a review[J].Molecular Nutrition & Food Research,2011,55(1):83-95.
[8] GANHÃO R,MORCUENDE D,ESTÉVEZ M.Tryptophan depletion and formation of α-aminoadipic and γ-glutamic semialdehydes in porcine burger patties with added phenolic-rich fruit extracts[J].Journal of Agricultural and Food Chemistry,2010,58(6):3541-3548.
[9] MOYLAN S,BERK M,DEAN O M,et al.Oxidative & nitrosative stress in depression:why so much stress?[J].Neuroscience & Biobehavioral Reviews,2014,45:46-62.
[10] FAYEMI P O,MUCHENJE V.Maternal slaughter at abattoirs:history,causes,cases and the meat industry[J].Springer Plus,2013,2(1):125.
[11] HUFF-LONERGAN E,LONERGAN S M.Mechanisms of water-holding capacity of meat:The postmortem biochemical structural changes[J].Meat Science,2005,71(1):194-204.
[12] YANG PG, FENG YJ, HAO Y, et al. Effects of continuous high tem-

perature stress on growth performance, carcass traits, nutrient content in longissimus dorsi muscle and muscle fiber characteristics of finishing pigs[J]. Chinese Journal of Animal Nutrition, 2014, 26(9):2503-2512.
[13] YAN X, BAI XM, HU XD, et al. Effects of electric shock driving stress on meat quality and physiological and biochemical indicators of Pietrain and Northeast Min pigs[J]. Animal Husbandry and Veterinary Medicine, 2015, 47(10):66-69.
[14] WARNER R D,DUNSHEA F R,PONNAMPALAM E N,et al.Effects of nitric oxide and oxidation in vivo and postmortem on meat tenderness[J].Meat Science,2005,71(1):205-217.
[15] HUANG M, LUO X. Role of endogenous proteases in meat tenderization (review)[J]. Meat Research, 1999(2):9-11.
[16] YIN JD, LI DF. Molecular mechanisms of pork quality formation and nutritional regulation[J]. Chinese Journal of Animal Nutrition, 2014, 26(10):2979-
[17] CUI YJ. Effects of heat stress and oxidative stress on skeletal muscle metabolism of finishing pigs and the regulatory role of lipoic acid[D]. PhD Thesis. Beijing: Chinese Academy of Agricultural Sciences, 2016:61-75.
[18] PAN JH. Study on the relationship between frozen storage methods, pork protein oxidation and pork quality[D]. Master' s Thesis. Wuxi: Jiangnan University, 2011:9-36.
[19] LI QP, QIAO XH, WANG XD. Effects of dietary vitamin E supplementation on pork quality[J]. Chinese Journal of Animal Science, 2003, 39(5):34-35.
[20] ZHANG YW, LUO HL, LIU K, et al. Calpain-mediated protein degradation mechanism of licorice extract in reducing muscle drip loss[C]//Proceedings of the 7th China Feed Nutrition Symposium of Animal Nutrition Branch of Chinese Association of Animal Science and Veterinary Medicine. Zhengzhou: Chinese Association of Animal Science and Veterinary Medicine, 2014.
[21] GE SY. Effects of vitamin E on mutton quality improvement and lipoprotein lipase activity[D]. Master' s Thesis. Beijing: China Agricultural University, 2011:17-18.
[22] WANG XH. Effects of VC and VE on antioxidant performance and meat oxidative stability of broilers[D]. Master' s Thesis. Yangling: Northwest A&F University, 2010:23-42.
[23] WANG XH, LIU FZ, NIU ZY, et al. Effects of VE on antioxidant performance and meat oxidative stability of broilers[J]. Acta Agriculturae Boreali-occidentalis Sinica, 2011, 20(2):1-7.
[24] MORRISSEY P A,BRANDON S,BUCKLEY D J,et al.Tissue content of α-tocopherol and oxidative stability of broilers receiving dietary α-tocopheryl acetate supplement for various periods pre-slaughter[J].British Poultry Science,1997,38(1):84-88.
[25] MANGELS A R,HOLDEN J M,BEECHER G R,et al.Carotenoid content of fruits and vegetables:an evaluation analytic data[J].Journal the American Dietetic Association,1993,93(3):284-296.
[26] JIANG HQ. Effects of lycopene on meat quality and antioxidant mechanism of Bamei mutton sheep[D]. PhD Thesis. Beijing: China Agricultural University, 2015:30-73.

[27] ZHANG T, CHEN YG, LUO JJ. Research progress of tea polyphenols in animal production[J]. Feed Review, 2013(3):16-19.
[28] CHAO YM, CHEN DW, YU B, et al. Effects of tea polyphenols on growth performance, antioxidant capacity, carcass quality and meat quality of finishing pigs[J]. Chinese Journal of Animal Nutrition, 2016, 28(12):3996-4005.
[29] YAO B, TU YY, WANG CH. Application study of tea polyphenols as a natural meat quality improver for finishing pigs[J]. Feed Industry, 2015, 36(20):12-14.
[30] HUANG T. Effects of honeysuckle extract on skeletal muscle fiber morphology and muscle quality of beef cattle under high summer temperature conditions[D]. Master' s Thesis. Nanchang: Jiangxi Agricultural University, 2015:22-30.
[31] ZHANG C,LUO J Q,YU B,et al.Dietary resveratrol supplementation improves meat quality of finishing pigs through changing muscle fiber characteristics and antioxidative status[J].Meat Science,2015,102:15-21.
[32] VERMA A K,RAJKUMAR V,BANERJEE R,et al.Guava (Psidium guajava L.) Powder as an Antioxidant dietary fibre in sheep meat nuggets[J].Asian-Australasian Journal of Animal Sciences,2013,26(6):886-895.
[33] LI WL. Effects of mulberry leaves on growth performance, blood biochemical indices, immune and antioxidant functions, and meat quality of mutton sheep[D]. Master' s Thesis. Hohhot: Inner Mongolia Agricultural University, 2012:21-22.
[34] SIMITZIS P E,DELIGEORGIS S G,BIZELIS J A,et al.Effect of dietary oregano oil supplementation on lamb meat characteristics[J].Meat Science,2008,79(2):217-223.
[35] SIMITZIS P E,SYMEON G K,CHARISMIADOU M A,et al.The effects of dietary oregano oil supplementation on pig meat characteristics[J].Meat Science,2010,84(4):670-676.
[36] GUO ZY. Effects of α-lipoic acid on antioxidant capacity of broilers and its mechanism[D]. Master' s Thesis. Nanjing: Nanjing Agricultural University, 2014.
[37] ZHANG TY, XU HP, ZENG YQ, et al. Effects of feeding different doses of Lactobacillus solution on meat quality characteristics and antioxidant capacity of finishing pigs[J]. Swine Production, 2014(1):41-43.
[38] BIAN LQ, YUAN D, LIU XJ, et al. Effects of dihydropyridine on growth performance, meat quality and muscle tissue antioxidant capacity of finishing pigs[J]. Henan Animal Husbandry and Veterinary Medicine: Comprehensive Edition, 2009, 30(5):5-7.
[39] LI J, ZHOU QF, TONG XL, et al. Effects of dietary rice bran and antioxidant supplementation on growth performance and meat quality of finishing pigs[J]. Cereal and Feed Industry, 2010(1):42-45.

Note: Figure translations are in progress. See original paper for figures.