

Effects of Muscle Fatty Acids on Meat Quality in Ruminants and Their Regulatory Factors: Post-print

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Abstract

The content and composition of fatty acids in muscle influence meat quality and consumer health to a certain extent. Meat products from ruminants are the primary source of health-promoting conjugated linoleic acid. Therefore, elucidating the formation mechanism and regulatory approaches of muscle fatty acids in ruminants is essential. This review primarily focuses on the regulatory factors of muscle fatty acids in ruminants and the effects of muscle fatty acids on meat flavor, oxidative stability, and meat color, aiming to provide references for improving muscle fatty acids in ruminants.

Full Text

Effects of Muscle Fatty Acids on Meat Quality and Their Regulatory Factors in Ruminants

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Abstract: The content and composition of fatty acids in muscle influence meat quality and consumer health to a considerable extent. Ruminant meat products represent the primary source of health-promoting conjugated linoleic acid (CLA). Therefore, elucidating the formation mechanisms and regulatory approaches of muscle fatty acids in ruminants is essential. This review summarizes the regulatory factors of muscle fatty acids in ruminants and their effects on meat flavor, oxidation stability, and color, aiming to provide a reference for improving muscle fatty acid profiles in ruminants.

Keywords: ruminant; muscle fatty acid; meat quality; regulatory factor

With continuous improvement in living standards, consumers demand higher meat quality, emphasizing not only taste and tenderness but also health benefits. Ruminant meat products are favored for their low cholesterol, low fat, and rich nutritional content. The deposition of muscle fatty acids in animals is influenced by multiple factors, including nutritional regulation, breed, age, sex, and genetics. Research indicates that muscle fatty acid content and composition are important indicators reflecting meat quality. Fatty acids in muscle serve as crucial precursors for meat flavor and are closely related to human health. Therefore, investigating the formation mechanisms and influencing factors of muscle fatty acids holds significant importance for improving meat quality. This paper focuses on discussing the effects of muscle fatty acids on meat quality and their regulatory factors in ruminants.

1 Effects of Fatty Acids on Meat Quality

Meat quality encompasses various aspects, primarily including physical parameters such as color and water-holding capacity, chemical parameters such as antioxidant capacity, and sensory attributes like flavor and juiciness. The influence of fatty acids on meat quality is mainly manifested in flavor and antioxidant capacity.

1.1 Fatty Acids and Flavor

Meat flavor can be divided into two categories: a general meaty aroma common to all meats, and a species-specific distinctive flavor. Research shows that the Maillard reaction between amino acids and carbonyl compounds forms the typical aroma of cooked meat, while different short-chain fatty acids produced by fat degradation [such as caproic acid (C6:0) and caprylic acid (C8:0)] are the main substances responsible for species-specific flavors. Studies have reported a significant positive correlation between palmitoleic acid (C16:1) content and meat flavor in Mongolian sheep. In naturally grazed Sunit sheep, higher oleic acid (C18:1) content and oleic-to-linoleic acid ratio (C18:1:C18:2) correlate with richer and more delicious mutton flavor. Meanwhile, stearic acid (C18:0) content is associated with mutton odor, particularly when high levels of C18:0 in subcutaneous fat intensify the characteristic smell. Research on Merino sheep also indicates that off-flavor increases with higher C18:0 content in meat, reducing consumer acceptance. Studies show that linolenic acid (C18:3) in mutton produces derivatives such as 2-pentene during processing, significantly increasing fishy odor. Additionally, short-chain saturated fatty acids (SCFA) in sheep body fat show a significant positive correlation with mutton odor; increased levels of capric acid (C10:0) and butyric acid (C4:0) significantly intensify the characteristic smell. In summary, C16:1, C18:1, and linoleic acid (C18:2) play major roles in meat flavor, whereas C18:0, C18:3, C10:0, and C4:0 show signif-

icant positive correlations with off-flavors. Therefore, modifying muscle fatty acid content and composition represents an important approach for regulating mutton flavor.

1.2 Fatty Acids and Oxidation Stability

Under normal physiological conditions, the redox system in livestock maintains dynamic equilibrium, protecting the body from free radical attack. However, after slaughter, this balance is disrupted, shifting toward oxidation. Fat oxidation is primarily influenced by the content of readily oxidizable polyunsaturated fatty acids (PUFA) in muscle. Research indicates that beef antioxidant stability, shelf life, and meat color lightness decrease significantly with increased ω -3 PUFA content, ultimately affecting consumer acceptance. Different PUFA types exhibit varying antioxidant capacities; ω -3 PUFA possess higher antioxidant capacity than ω -6 PUFA, potentially extending meat shelf life. Furthermore, medium- and long-chain unsaturated fatty acids (C8-C17) and branched-chain fatty acids (BCFA) have lower melting points, and increased levels of these fatty acids can significantly improve meat juiciness and overall palatability. Saturated fatty acids (SFA) are known to have higher melting points, greater density, and lower oxidation susceptibility compared to unsaturated fatty acids (UFA). Therefore, it is speculated that higher SFA content in muscle may enhance antioxidant capacity, favoring long-term meat storage. However, elevated levels of most SFAs such as lauric acid (C12:0), myristic acid (C14:0), and palmitic acid (C16:0) are detrimental to human health, as they increase low-density lipoprotein and blood cholesterol levels, potentially causing cardiovascular diseases like atherosclerosis and coronary heart disease. Studies suggest that the optimal dietary ratio of saturated to monounsaturated to polyunsaturated fatty acids (SFA:MUFA:PUFA) for human health is 1:1:1, indicating that an appropriate balance between SFA and UFA is more beneficial for human health.

2 Regulatory Factors of Muscle Fatty Acids

2.1 Genetic Regulation

Genetic effects on intramuscular fat deposition can be divided into positive and negative regulation. Fatty acids are important components of fat, and the synthesis and catabolism processes in animal adipocytes directly affect intramuscular fatty acid content and composition.

2.1.1 Genes Up-regulating Intramuscular Fat Deposition Lipoprotein lipase (LPL) is a rate-limiting enzyme in triglyceride metabolism that plays an important role in regulating adipocyte maturation and differentiation. Fatty acid synthase (FAS) is a key enzyme in fatty acid synthesis, primarily catalyzing saturated fatty acid synthesis. Studies show that LPL and FAS expression promotes intramuscular fat deposition in different muscle sites of Hu sheep. Acetyl-CoA carboxylase (ACC) has two isoforms in ruminants: ACC- α

(ACACA) is the rate-limiting enzyme for long-chain fatty acid (LCFA) synthesis, catalyzing acetyl-CoA to malonyl-CoA; ACC- β (ACACB) primarily promotes malonyl-CoA generation and regulates mitochondrial fatty acid oxidation. Research indicates that ACC affects C16:0 and LCFA synthesis, and its expression level shows a significant positive correlation with intramuscular fat deposition. Therefore, LPL, FAS, and ACC up-regulate intramuscular fat deposition.

2.1.2 Genes Down-regulating Intramuscular Fat Deposition Carnitine palmitoyltransferase 1 (CPT1) is a key enzyme controlling LCFA oxidation, participating in fatty acid β -oxidation and accelerating tissue fat degradation, ultimately significantly reducing fat deposition. Preadipocyte factor 1 (Pref-1) is highly expressed in preadipocytes and decreases during adipocyte differentiation, with no expression in mature adipocytes. Therefore, down-regulating Pref-1 expression can significantly enhance adipocyte differentiation. Hormone-sensitive lipase (HSL) catalyzes triglyceride hydrolysis to diglycerides and subsequently to monoglycerides, serving as a rate-limiting enzyme in fat degradation. It also hydrolyzes monoglycerides to free fatty acids (FFA), making it a key enzyme regulating adipose tissue lipolysis. Studies show that Pref-1 and HSL expression levels are negatively correlated with intramuscular fat deposition and decrease with increasing body weight in Sunit lambs. Leptin can significantly reduce fat deposition by stimulating fat oxidation and decomposition in tissues. The leptin receptor (OBR) is a transmembrane protein with high affinity for leptin. Uncoupling protein 3 (UCP3) is a proton transporter located in the mitochondrial inner membrane, and increased UCP3 in muscle significantly enhances fat oxidation levels. Research indicates that OBR and UCP3 expression down-regulates intramuscular fat deposition in Hu sheep. Peroxisome proliferator-activated receptor γ (PPAR γ) is an important factor promoting adipocyte differentiation and fat metabolism. Adipocyte determination and differentiation factor I (ADDI) is a crucial transcription factor for fat synthesis-related genes. Studies show that PPAR γ and ADDI expression levels are significantly negatively correlated with intramuscular fat deposition in lambs. In summary, CPT1, HSL, Pref-1, OBR, UCP3, PPAR γ , and ADDI down-regulate intramuscular fat deposition.

2.1.3 Fatty Acid Desaturase (FAD) Genes FAD catalyzes the dehydrogenation of C-C bonds at specific positions in fatty acyl chains to form C=C bonds, serving as a key enzyme for PUFA synthesis. FAD comprises a large family with many subtypes. Among them, fatty acid desaturase 1 (FADS1) and fatty acid desaturase 2 (FADS2) control Δ 5 and Δ 6 desaturase activities, respectively, which represent the capacity to elongate C18:2 and C18:3 to their long-chain PUFA derivatives. Additionally, grazing can significantly increase Δ 5 and Δ 6 desaturase activities. Fatty acyl desaturase 2 (Fad2) primarily regulates Δ 4 desaturase activity, which represents the conversion capacity from C22:5 to C22:6. Therefore, FADS1, FADS2, and Fad2 can control the elongation of C18:2, C18:3, and C22:5 to their long-chain PUFA derivatives by regulating Δ 5, Δ 6,

and $\Delta 4$ desaturase activities. Stearoyl-CoA desaturase (SCD) is a key enzyme for endogenous CLA synthesis in ruminant meat products. Studies show that CLA content in lamb meat increases significantly with SCD expression levels, and SCD can serve as a candidate gene for fatty acid genetic variation. In summary, FADS1, FADS2, Fad2, and SCD are enzyme genes responsible for muscle fatty acid desaturation.

2.2 Nutritional Regulation

2.2.1 Dietary Effects Diet is an important pathway for regulating muscle fatty acids. Dietary linseed supplementation significantly increases muscle ω -3 PUFA, ω -6 PUFA, and CLA contents, with 10% linseed supplementation making lamb CLA and PUFA contents more aligned with human health standards. Moreover, simultaneous supplementation of linseed and vitamin E can significantly reduce the ω -3PUFA: ω -6PUFA ratio, improving lamb quality. Studies show that dietary isoflavones and CLA significantly increase SCD activity in muscle, while α -tocopherol supplementation significantly increases C18:1 content, both ultimately enhancing CLA content in lamb. Catechin and mulberry leaf supplementation inhibit rumen microbial hydrogenation of PUFA, thereby significantly increasing PUFA content in lamb. Dietary tannins affect the rumen microbial hydrogenation step from C18:1 to C18:0, significantly increasing C18:1 content in muscle. Additionally, oil supplementation affects muscle fatty acids. Research indicates that dietary fish oil and sunflower oil both significantly increase muscle CLA content, possibly due to significantly reduced numbers of *Clostridium proteoclasticum* under these conditions, leading to increased production of vaccenic acid (TVA), a CLA precursor. In summary, different diets may affect muscle fatty acid content and composition by altering SCD activity, microbial hydrogenation steps, and microbial populations.

2.2.2 Grazing Management Grazing allows ruminants to access diverse forage types, thereby affecting muscle fatty acid content and composition, making it an effective regulatory approach. Research shows that grazing improves muscle fatty acid profiles to better meet human dietary standards. Previous studies indicate that grazing significantly increases muscle CLA and ω -3 PUFA contents compared to indoor feeding, likely because forage is richer in PUFA and SCD than concentrates. Additionally, forage is more easily digested and has shorter retention time in the rumen, reducing microbial hydrogenation time for PUFA and producing more rumen-bypass PUFA. Furthermore, increasing grazing intensity and duration can optimize the ω -3PUFA: ω -6PUFA ratio for human health. Studies show that forage species and ratios during grazing significantly affect muscle contents of monounsaturated fatty acids (MUFA), PUFA, C18:1, C18:2, C18:3, and other fatty acids, with legume-based diets significantly improving lamb nutritional value. Comparing organic pasture grazing with conventional grazing, researchers found the former produces more human-beneficial fatty acids such as ω -3 PUFA, docosapentaenoic acid (DPA), and docosahexaenoic acid (DHA). The proposed reason is that organic pastures contain more

PUFA-rich, high-quality forage, generating more human-beneficial fatty acids. In summary, grazing produces more PUFA mainly through two mechanisms: 1) grazing animals consume more fresh forage, which is richer in ω -3 PUFA than grains, increasing rumen hydrogenation substrate concentration and producing more PUFA; and 2) higher SCD activity in forage significantly increases muscle PUFA, especially CLA content.

2.3 Other Factors

2.3.1 Breed Studies show that under the same indoor feeding conditions, Tan sheep have significantly higher total essential fatty acids (EFA) and DPA and DHA contents than Small-tailed Han sheep. Additionally, C18:0 content in tail fat of Large-tailed Han sheep is significantly higher than in Small-tailed Han sheep. Research on major local sheep breeds in southern Xinjiang reveals large differences in muscle PUFA:SFA ratios: Duolang (0.072) > Hetian (0.064) > Karakul (0.053) > Kirgiz (0.046). In conclusion, genetic background differences cause variations in fatty acid content among sheep breeds.

2.3.2 Sex Research indicates that sex primarily affects fatty acids in intermuscular fat. Studies show that ram muscle contains significantly higher PUFA and lower SFA and C16:0 than ewe muscle. Castration is also an effective method for improving meat quality. Research finds that castrated bulls have significantly higher C16:0 and C18:1 contents than intact bulls. The reasons may include: 1) meat quality is related to androgen regulation, with reduced androgen secretion after castration; and 2) castration significantly increases C18:1 content, altering muscle fatty acid composition, though the specific regulatory mechanisms remain unclear and require further investigation.

2.3.3 Age Postnatal tissue development follows the sequence of bone, muscle, and fat, creating a corresponding relationship between fatty acids and age. Research shows that lamb muscle contains significantly higher PUFA and MUFA than adult sheep, while adult sheep have higher SFA content, especially C18:0 which correlates with mutton odor. Additionally, BCFA content is an important indicator for distinguishing lamb from adult sheep meat, with 4-methyloctanoic acid, 4-methylnonanoic acid, and 4-ethyloctanoic acid generally increasing with age, and higher levels of these three BCFAs intensifying mutton odor. Therefore, lamb meat has relatively lower off-flavor. In summary, lamb muscle is rich in UFA, and odor-related fatty acid content is positively correlated with animal age.

Conclusion

In conclusion, regulating meat quality attributes such as flavor, antioxidant capacity, and color can be achieved by altering fatty acid content and composition in ruminant muscle. However, few studies have examined the effects of muscle fatty acids on water-holding capacity, cooking loss, pH, and changes in fatty

acid content and composition in processed meat products, with the latter being a noteworthy research direction. Ruminant muscle fatty acids are influenced by numerous factors, including nutritional regulation, genetics, breed, sex, and age. In practical production, nutritional factors should be fully utilized to regulate muscle fatty acids and improve their content and composition. Furthermore, the regulatory mechanisms of genes responsible for fat deposition on muscle fatty acids require further elucidation, and more FAD genes promoting elongation of fatty acids to long-chain PUFA need to be identified.

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