Effects of Rumen-Protected Unsaturated Fat on Growth Performance and Beef Fatty Acid Composition in Angus Cattle (Postprint)

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Abstract

This experiment aimed to investigate the effects of rumen-protected unsaturated fat on growth performance and beef fatty acid composition in Angus cattle. Twenty-four Angus steers with an average body weight of (447.78±2.53) kg and aged 17–18 months were selected and randomly divided into 4 groups with 6 steers per group. Group 1 served as the control group and was fed a basal diet, while groups 2, 3, and 4 were supplemented with rumen-protected unsaturated fat at 2.0%, 4.0%, and 6.0% of dry matter intake, respectively. The total experimental period was 77 days, including a 10-day preliminary period and a 67-day formal experimental period.

The results showed that: 1) No significant differences were observed among groups in average daily gain, average daily feed intake, and feed conversion ratio ($P>0.05$). 2) The apparent digestibility of crude protein in group 3 was significantly higher than that in groups 1 and 4 ($P<0.05$); the apparent digestibility of ether extract in groups 3 and 4 was significantly higher than that in group 1 ($P<0.05$); and the apparent digestibility of acid detergent fiber in groups 1 and 2 was significantly higher than that in group 4 ($P<0.05$).

3) The backfat thickness of group 4 was significantly higher than that of group 1 ($P<0.05$). No significant differences were found among groups in dressing percentage, meat yield percentage, or loin eye area ($P>0.05$). Additionally, no significant differences were observed among groups in pH, shear force, cooking loss, drip loss, meat color, or muscle chemical composition ($P>0.05$).

4) The C18:0 content in the longissimus dorsi muscle of group 1 was significantly higher than that of groups 2 and 3 ($P<0.05$), while the C20:4n6 content in group 2 was significantly higher than that in groups 1 and 4

(P<0.05). Compared with group 1, the saturated fatty acid content in groups 2, 3, and 4 decreased by 8.41%, 10.26%, and 5.48%, respectively; monounsaturated fatty acid content increased by 6.37%, 9.41%, and 6.72%, respectively; and polyunsaturated fatty acid content increased by 69.78%, 33.19%, and 9.36%, respectively; however, these differences were not significant (P>0.05). 5) During the early fattening period, serum malondialdehyde content in groups 2, 3, and 4 was significantly lower than that in group 1 (P<0.05); during the late fattening period, serum malondialdehyde content in groups 3 and 4 was significantly lower than that in group 1 (P<0.05).

Under the conditions of this experiment, dietary supplementation with rumen-protected unsaturated fat had no significant effect on average daily feed intake or average daily gain in beef cattle, but was beneficial for improving the apparent digestibility of dietary crude protein and ether extract, increasing backfat thickness and antioxidant capacity, and improving beef fatty acid composition. Taking all factors into consideration, the optimal supplementation level of rumen-protected unsaturated fat in Angus cattle diets was 4.0% of dietary dry matter intake.

Full Text

Effects of Rumen-Protected Unsaturated Fat on Growth Performance and Fatty Acid Composition of Beef in Angus Cattle

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Abstract

This study investigated the effects of rumen-protected unsaturated fat (RPUF) on growth performance and fatty acid composition in Angus beef cattle. Twenty-four Angus steers with an average body weight of (447.78±2.53) kg, aged 17–18 months, were randomly divided into four groups of six animals each. Group 1 served as the control and received a basal diet, while groups 2, 3, and 4 received diets supplemented with RPUF at 2.0%, 4.0%, and 6.0% of dry matter intake, respectively. The 77-day trial consisted of a 10-day preliminary period followed by a 67-day formal experimental period. The results showed: (1) No significant differences were observed among groups in average daily gain, average daily feed intake, or feed-to-gain ratio (P>0.05). (2) The apparent digestibility of crude protein in group 3 was significantly higher than in groups 1 and

4 (P<0.05), while the apparent digestibility of ether extract in groups 3 and 4 was significantly higher than in group 1 (P<0.05). The apparent digestibility of acid detergent fiber in groups 1 and 2 was significantly higher than in group 4 (P<0.05). (3) Backfat thickness in group 4 was significantly greater than in group 1 (P<0.05), though no significant differences were found among groups in dressing percentage, net meat percentage, or eye muscle area (P>0.05). Similarly, no significant differences were detected in pH, shear force, cooking loss, drip loss, meat color, or muscle chemical composition (P>0.05). (4) The C18:0 content in the longissimus dorsi muscle of group 1 was significantly higher than in groups 2 and 3 (P<0.05), while the C20:4n6 content in group 2 was significantly higher than in groups 1 and 4 (P<0.05). Compared with group 1, the saturated fatty acid content decreased by 8.41%, 10.26%, and 5.48% in groups 2, 3, and 4, respectively; monounsaturated fatty acid content increased by 6.37%, 9.41%, and 6.72%; and polyunsaturated fatty acid content increased by 69.78%, 33.19%, and 9.36%, though these differences were not statistically significant (P>0.05). (5) During the early fattening stage, serum malondialdehyde (MDA) content in groups 2, 3, and 4 was significantly lower than in group 1 (P<0.05), while during the later fattening stage, serum MDA in groups 3 and 4 was significantly lower than in group 1 (P<0.05). Under the conditions of this experiment, dietary supplementation with RPUF had no significant effect on feed intake or daily gain in beef cattle, but improved the apparent digestibility of crude protein and ether extract, increased backfat thickness and antioxidant capacity, and improved fatty acid composition. Based on comprehensive evaluation of growth performance, nutrient digestibility, slaughter characteristics, meat quality, and fatty acid profile, the optimal supplementation level of RPUF in Angus cattle diets is 4.0% of dry matter intake.

Keywords: rumen-protected unsaturated fat; beef cattle; growth performance; fatty acid composition

Introduction

Beef is a major meat product worldwide, with saturated fatty acids comprising over 50% of total fatty acids in conventional beef. Saturated fatty acids can increase low-density lipoprotein cholesterol in human blood, posing potential cardiovascular health risks. Supplementing diets with linseed rich in polyunsaturated fatty acids (PUFA) can increase intramuscular fat content, significantly improve muscle and fat color, enhance beef flavor, increase n-3 fatty acid content in beef, and reduce the n-6/n-3 PUFA ratio. PUFA influences the composition and content of phospholipid fatty acids in cell membranes, affecting membrane fluidity and receptor function. Under certain conditions, PUFA can be released from membrane phospholipid pools and converted to free forms, metabolizing into biologically active lipid mediators that protect animals from atherosclerosis, reduce blood triglyceride levels, inhibit platelet aggregation, prevent thrombosis, and decrease cardiovascular disease incidence. PUFA can also produce anti-

inflammatory lipid mediators. Feeding rats with methylcholanthrene-induced sarcoma using diets containing eicosapentaenoic acid (EPA) reduced tumor volume, as EPA exerted anti-tumor effects by inhibiting vascular endothelial factor expression. Additionally, PUFA can regulate gene expression of carnitine palmitoyltransferase (CPT) and 3-hydroxy-3-methylglutaryl-CoA synthase (HMGCS) in hepatocytes, increasing mRNA levels by 2–4 fold. Feeding ruminants with vegetable oils rich in C18 PUFA significantly inhibits methane production, which is environmentally significant, though certain fatty acids in vegetable oils can be toxic to rumen microorganisms, particularly linolenic acid, which reduces protozoa and methanogen populations. Rumen-protected fat avoids interference with rumen microorganisms, reduces inhibition of rumen fermentation, and enables production of beef rich in essential fatty acids, thereby improving product quality. Current research has focused on direct dietary addition of various fat sources or optimal supplementation levels of rumen-protected saturated fatty acids, as well as effects of rumen-protected fat made from linseed oil on rumen fermentation and urinary purine derivatives, and impacts on nutrient apparent digestibility and nitrogen retention. However, few studies have examined the effects of varying supplementation levels of rumen-protected unsaturated fat on growth performance and beef fatty acid composition. This experiment aimed to investigate the effects of different supplementation levels of calcium salts of unsaturated fatty acids on growth performance and muscle chemical composition and fatty acid content in beef cattle.

Materials and Methods

1.1 Experimental Materials, Animals, and Design The rumen-protected unsaturated fat was developed by the College of Animal Science and Veterinary Medicine at Shanxi Agricultural University, using linseed oil as raw material in the form of calcium salts of unsaturated fatty acids. The product contained 97.00% dry matter, with 83.14% fat content on a dry matter basis. Specific fatty acid composition included: C12:0, C14:0, C16:0, and C16:1 at 0.00%; C18:0 at 3.00%; C18:1 at 27.77%; C18:2 at 26.83%; C18:3 at 24.93%; and other long-chain fatty acids at 0.61%. The average disappearance rates in the rumen were 5.15% and 8.63% at 24 and 48 hours, respectively.

Twenty-four Angus steers aged 15–17 months with an average body weight of (447.78±2.53) kg were randomly allocated to four groups following a completely randomized design. The groups received diets containing 0.0%, 2.0%, 4.0%, and 6.0% RPUF (with consistent nutrient provision except for net energy for gain and feed intake), with six replicates per group (one animal per replicate). The trial was conducted at Shanxi Wanmu Technology Co., Ltd. from July 13 to September 28, 2016, comprising a 10-day preliminary period and a 67-day formal experimental period.

1.2 Experimental Diets and Management Experimental diets were formulated according to nutrient requirements calculated based on body weight and a target daily gain of 1.2 kg. Diet composition and nutrient levels are presented in Table 1 . The net energy value of RPUF was calculated based on the apparent digestibility of dietary ether extract, from which digestible energy was determined according to fat content, followed by breed correction and calculation of comprehensive net energy. Cattle were fed individually using neck-controlled single stalls, with neck chains combined with tethering during the digestibility trial. The concentrate-to-forage ratio was 67:33 throughout the experiment, with feeding at 06:30 and 15:00 daily and free access to water. All animals were limit-fed at 9.90 kg dry matter intake during the early period and 10.30 kg during the later period, with RPUF added on this basis.

1.3 Sample Collection, Measurements, and Methods Body weight was recorded as the average of two consecutive days of fasting weights before morning feeding at the beginning and end of the trial. Daily feed intake and refusals were recorded, and diet and refusal samples were collected weekly for nutrient analysis to calculate apparent digestibility. Blood samples were collected on days 34 and 67 of the formal period to prepare serum for malondialdehyde (MDA) determination.

From day 24 of the formal period, cattle were restricted to pen areas after feeding (with free water access) to adapt to fecal collection requirements for digestibility trials. Total fecal collection was conducted from days 30–34 using covered plastic buckets. Feces were weighed, and 10% of the total weight was sampled. For each 100 g sample, 20 mL of 10% tartaric acid was added, and the 5-day fecal collection for each animal was mixed and stored at -20°C for subsequent analysis of dry matter (DM), organic matter (OM), crude protein (CP), ether extract (EE), crude fiber (CF), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Moisture content was determined by constant temperature drying at 105°C (GB 5009.3-2010), crude ash by muffle furnace incineration at 550°C (GB 5009.4-2010), CP by Kjeldahl method (GB 5009.5-2010), EE by Soxhlet extraction (GB 5009.6-2010), and NDF and ADF according to Van Soest et al. Nitrogen-free extract was calculated, and apparent digestibility of each nutrient was determined.

After the trial, cattle were fasted for 24 hours and deprived of water for 12 hours before slaughter. Pre-slaughter live weight, carcass weight, net meat weight, backfat thickness, and eye muscle area were measured. Carcasses were aged at 0–4°C for 72 hours. A 1-kg sample of longissimus dorsi muscle was collected near the 12th–13th thoracic vertebrae from the left carcass side, divided into two portions: one for meat quality analysis and the other rapidly frozen in liquid nitrogen and stored at -80°C for chemical composition and fatty acid analysis.

Meat pH was measured as the average of six readings using a handheld pH meter. Shear force was determined using a C-LM tenderness meter. Cooking loss was measured on approximately 3 cm × 3 cm × 6 cm meat blocks sealed in cooking

bags, heated in an 80°C water bath until internal temperature reached 70°C, then cooled to room temperature; cooking loss was calculated as the percentage of weight loss relative to initial weight. Drip loss was determined on cylindrical samples (2.523 cm diameter, 1 cm height) placed between gauze and 18 layers of neutral filter paper under 35 kg pressure for 5 minutes. Meat color was measured using a colorimeter and averaged. Backfat thickness was measured with calipers at 3/4 of the eye muscle length on the vertical plane. Eye muscle area was traced on tracing paper and calculated using a planimeter. For fatty acid analysis, 4 g of air-dried minced meat was placed in a 250-mL Soxhlet extractor with 100 mL petroleum ether and refluxed for 8 hours. The petroleum ether layer was separated, re-extracted with 40 mL petroleum ether, and the combined extracts were washed once each with saturated NaCl and distilled water, dried overnight with anhydrous Na SO , and evaporated using a rotary evaporator. Fatty acid methyl esters were prepared by mixing 0.2 mL fat with 1.0 mL ether-hexane (2:1), 1.0 mL methanol, and 1.0 mL KOH-CH OH (0.8 mol/L), shaking, standing for 5 minutes, adding distilled water to volume, and analyzing the upper layer by gas chromatography-mass spectrometry (Shimadzu 2010). Chromatographic conditions: HP-5 elastic quartz capillary column (300 m × 25 mm × 0.25 m), injector temperature 280°C, split ratio 20:1, injection volume 0.2 L. Mass spectrometry conditions: EI ion source, ionization voltage 70 eV, ion source temperature 280°C, emission current 34.6 mA, scan range 30–500 amp. Serum MDA content was determined by spectrophotometry (MAPADA UV-1800) using the thiobarbituric acid method (GB5009.181-2016).

1.4 Calculation Methods Apparent digestibility of a nutrient (%) = 100 × (nutrient intake -nutrient excretion in feces) / nutrient intake
Dressing percentage (%) = 100 × carcass weight (kg) / pre-slaughter live weight (kg)
Net meat percentage (%) = 100 × net meat weight (kg) / pre-slaughter live weight (kg)
Cooking loss (%) or drip loss (%) = 100 × weight after cooking or pressure / original sample weight

1.5 Statistical Analysis Data were preliminarily analyzed using Excel 2010, followed by one-way ANOVA using the SAS 8.0 software package. Duncan' s multiple range test was applied for post-hoc comparisons, with $P < 0.05$ considered statistically significant.

Results

2.1 Effects of RPUF Supplementation on Growth Performance As shown in Table 2 , no significant differences were observed among groups in average daily gain, average daily feed intake, or feed-to-gain ratio ($P>0.05$).

However, RPUF supplementation tended to increase average daily gain while decreasing feed intake and feed-to-gain ratio.

2.2 Effects of RPUF Supplementation on Nutrient Apparent Digestibility Table 3 shows that apparent digestibility of crude protein in group 3 was significantly higher than in groups 1 and 4 ($P<0.05$), with no significant differences among other groups ($P>0.05$). Ether extract apparent digestibility in groups 3 and 4 was significantly higher than in group 1 ($P<0.05$), with no significant differences among remaining groups ($P>0.05$). Acid detergent fiber apparent digestibility in groups 1 and 2 was significantly higher than in group 4 ($P<0.05$), with no significant differences among other groups ($P>0.05$). No significant differences were detected among groups in apparent digestibility of nitrogen-free extract or neutral detergent fiber ($P>0.05$).

2.3 Effects of RPUF Supplementation on Slaughter Performance Table 4 indicates that backfat thickness in group 4 was significantly greater than in group 1 ($P<0.05$), with no significant differences among other groups ($P>0.05$). No significant differences were observed among groups in pre-slaughter live weight, carcass weight, net meat weight, dressing percentage, net meat percentage, or eye muscle area ($P>0.05$).

2.4 Effects of RPUF Supplementation on Meat Quality Table 5 demonstrates that no significant differences existed among groups in pH, shear force, cooking loss, drip loss, meat color, or muscle chemical composition ($P>0.05$). However, RPUF-supplemented groups showed numerically lower shear force, cooking loss, drip loss, and muscle ash content compared with group 1.

2.5 Effects of RPUF Supplementation on Fatty Acid Composition Table 6 reveals that C18:0 content in group 1 was significantly higher than in groups 2 and 3 ($P<0.05$), but not significantly different from group 4 ($P>0.05$). C18:1n9c content in group 3 was significantly higher than in group 1 ($P<0.05$), with no significant differences from groups 2 and 4 ($P>0.05$). C20:4n6 content in group 2 was significantly higher than in groups 1 and 4 ($P<0.05$), with no significant difference from group 3 ($P>0.05$). No significant differences were detected among groups in total saturated, monounsaturated, or polyunsaturated fatty acid contents ($P>0.05$), though group 1 had the highest saturated fatty acid content and the lowest monounsaturated and polyunsaturated fatty acid contents. Following RPUF supplementation, groups 2, 3, and 4 showed decreases in saturated fatty acids of 8.41%, 10.26%, and 5.48%, increases in monounsaturated fatty acids of 6.37%, 9.41%, and 6.72%, and increases in polyunsaturated fatty acids of 69.78%, 33.19%, and 9.36%, respectively, compared with group 1.

2.6 Effects of RPUF Supplementation on Serum Malondialdehyde Content Table 7 shows that during the early fattening stage, serum MDA content in groups 2, 3, and 4 was significantly lower than in group 1 ($P<0.05$).

During the later fattening stage, serum MDA in groups 3 and 4 was significantly lower than in group 1 ($P<0.05$), with no significant differences between groups 1 and 2 or between groups 3 and 4 ($P>0.05$).

Discussion

Mangrum et al. reported that supplementing diets with high-oleic fat or rumen-protected unsaturated fat did not significantly affect average daily gain in fattening cattle, consistent with our findings. In our study, RPUF was added as a supplement, resulting in iso-nitrogenous but non-isoenergetic diets. The lack of significant differences in average daily gain may be attributed to two factors: first, energy requirements exceeded crude protein requirements during the fattening stage, and second, the experimental animals were in a peak growth phase.

Our results indicate that RPUF supplementation did not significantly affect NDF apparent digestibility but significantly influenced ADF apparent digestibility, consistent with findings by Zhao Guangyong et al., Zheng Xiaozhong et al. (at equivalent supplementation levels), and Xing Zhuang et al. Zheng Xiaozhong et al. reported that excessive RPUF supplementation (>9%) significantly reduced rumen degradation of ADF and NDF. High dietary fat levels may block contact between rumen microorganisms and feed particles, and since the rumen is the primary site for NDF and ADF digestion and ADF digestibility is generally lower than NDF, overall carbohydrate digestibility may be adversely affected. Ether extract apparent digestibility increased significantly with increasing calcium salt levels of unsaturated fatty acids, consistent with results from Zheng Xiaozhong et al. and Xing Zhuang et al. The unsaturated fatty acid calcium salts used in this experiment were long-chain fatty acids that could be directly absorbed in the small intestine, significantly improving the efficiency of long-chain fatty acid synthesis compared with acetate-based synthesis.

Dressing percentage and net meat percentage are important indicators of animal growth and slaughter performance. Studies have reported dressing percentages of 60–65% for Angus cattle. In our trial, no significant differences were observed among groups, with an average dressing percentage of 55.56% (range 55.12–55.79%), which is lower than 60%. This may be attributed to lower slaughter weight and differences in slaughter methods, as modern mechanical skinning tends to leave more subcutaneous fat on the hide, resulting in lower dressing percentages. When protein and net energy intake exceed requirements for normal growth and maintenance, the excess nutrients are deposited as body fat, and subcutaneous fat deposition is an essential stage in beef cattle fattening. RPUF supplementation increased dietary net energy, thereby increasing backfat thickness. Groups 2, 3, and 4 showed numerically lower cooking loss and drip loss than group 1, with groups 2 and 3 showing the best results, possibly due to the effects of rumen-protected unsaturated fatty acids. Both cooking loss and

drip loss are related to biological membrane integrity, which depends on phospholipids rich in polyunsaturated fatty acids that are susceptible to oxidation. Disruption of normal membrane structure allows intracellular fluid leakage, and essential fatty acid deficiency reduces membrane stability and increases water permeability. Dietary PUFA can influence membrane phospholipid composition, increase -3 fatty acids in beef, and improve antioxidant capacity of subcutaneous and intramuscular fat, thereby protecting against oxidative damage during cooking and mechanical stress and improving water-holding capacity.

Our results show that groups 2, 3, and 4 had lower C18:0 content but higher C18:1n9c and C16:1n7 content in longissimus dorsi muscle than group 1, likely due to de novo fatty acid synthesis. Animals can only synthesize n-7 and n-9 monounsaturated fatty acids from corresponding saturated fatty acids (palmitic and stearic acid). Given that linseed oil contains 50–54% -linolenic acid and 16% linoleic acid (primarily C18 fatty acids), this may explain why C16:0 content in groups 2, 3, and 4 was similar to group 1, resulting in lower saturated fatty acid content in these groups. The higher polyunsaturated fatty acid content in groups 2, 3, and 4, particularly C18:2n6c, C20:3n6, and C20:4n6, may result from RPUF supplementation or from desaturation and elongation of linoleic and linolenic acid.

Reactive oxygen species (ROS) generated by metal induction can oxidize polyunsaturated fatty acid phosphate residues in cell membranes, causing selective loss of unsaturated fatty acids and relative increase in saturated fatty acids that maintain membrane rigidity, leading to membrane structural damage. MDA is produced during decomposition of lipid peroxides and is commonly used as an indicator of oxidative status. During damage repair, the oxidation chain reaction must be rapidly terminated and membranes repaired with alternative fatty acids to prevent structural and functional impairment. Dietary unsaturated fatty acids can repair biological membranes in a timely manner, preventing further lipid peroxide generation, which explains the lower serum MDA content in groups 2, 3, and 4. The later fattening stage occurred during hot August conditions, and heat stress accelerated ROS-mediated membrane oxidation, resulting in higher serum MDA during the later stage compared with the early stage.

Ladeira et al. reported that rumen-protected fat supplementation increased C18:1 and C18:3 content in longissimus dorsi muscle. Our results similarly showed that RPUF supplementation significantly increased C18:1n9c content and tended to reduce saturated fatty acid content. Additionally, our study demonstrated that RPUF supplementation significantly increased C20:4n6 content, while Ladeira et al. reported only a tendency for increase. This statistical difference may be attributed to variations in plant fat sources used. Regardless of the plant fat source, unsaturated fatty acids in rumen-protected form avoid ruminal hydrogenation and are ultimately deposited in tissues, altering muscle fatty acid composition.

Conclusion

Under the conditions of this experiment, dietary supplementation with rumen-protected unsaturated fatty acids increased backfat thickness, reduced C18:0 content in longissimus dorsi muscle, increased C20:4n6 and C18:1n9c content, improved fatty acid composition, enhanced antioxidant capacity, and tended to reduce shear force, cooking loss, and drip loss. Based on comprehensive evaluation of average daily gain, nutrient apparent digestibility, slaughter performance, meat quality, and fatty acid profile, the optimal supplementation level of rumen-protected unsaturated fat in Angus cattle diets is 4.0% of dry matter intake.

References

[1] LI Peng, SUN Jingxin, WANG Fengwu, et al. Analysis and functional evaluation of fatty acids in white yak meat[J]. Food Science, 2008, 29(4): 106-108.
[2] SUN Mingyuan. Food Nutrition[M]. Beijing: Science Press, 2006: 356-380.
[3] BARAHONA M, OLLETA J L, SAÑUDO C, et al. Effects of whole linseed and rumen-protected conjugated linoleic acid enriched diets on beef quality[J]. Animal, 2016, 10(4): 709-717.
[4] RAES K, BALCAEN A, CLAEYS E, et al. Effect of duration of feeding diets rich in n-3 PUFA to Belgian blue double-muscled young bulls, on the incorporation of long-chain n-3 and n-6 PUFA in the phospholipids and triglycerides of the longissimus thoracis[C]//Proceeding of the 48th International Congress of Meat Science and Technology. Rome: Elsevier, 2002: 724-725.
[5] SCOLLAN N D, DHANOA M S, CHOI N J, et al. Biohydrogenation and digestion of long chain fatty acids in steers fed on different sources of lipid[J]. Journal of Agricultural Science, 2001, 136(3): 345-355.
[6] SIMONS K, TOOMRE D. Lipid rafts and signal transduction[J]. Nature Reviews Molecular Cell Biology, 2000, 1(1): 31-39.
[7] STILLWELL W, WASSALL S R. Docosahexaenoic acid: membrane properties of a unique fatty acid[J]. Chemistry and Physics of Lipids, 2003, 126(1): 1-27.
[8] KUHN H, BANTHIYA S, VAN LEYEN K. Mammalian lipoxygenases their biological relevance[J]. Biochimica Biophysica (BBA)-Molecular Biology Lipids, 2015, 1851(4): 308-330.
[9] FERNANDEZ M L, WEST K L. Mechanisms by which dietary fatty acids modulate plasma lipids[J]. The Journal of Nutrition, 2005, 135(9): 2075-2078.
[10] GONG Jian, XIAO Min. Metabolism of polyunsaturated fatty acids and their regulation of inflammation[J]. Chinese Journal of Animal Nutrition, 2017, 29(1): 1-7.
[11] JHO D, BABCOCK T A, HELTON W S, et al. Omega-3 fatty acids: implications for the treatment of tumor-associated inflammation[J]. The American Surgeon, 2003, 69(1): 32-36.

[12] ZHANG Chunmei. Effects of vegetable oils and C18 unsaturated fatty acids on rumen methanogenesis and microecology[D]. Hangzhou: Zhejiang University, 2008.
[13] NRC. Nutrient requirements of dairy cattle[M]. 7th ed. Washington, D.C.: National Academy Press, 2001.
[14] FENG Yanglian. Ruminant Nutrition[M]. Beijing: Science Press, 2004: 401–419.
[15] YANG Shuli, WANG Jiaqi, HU Zhiyong, et al. Effects of dietary supplementation with soybean oil and linseed oil on rumen fermentation and main microbial populations in beef cattle[J]. Scientia Agricultura Sinica, 2007, 40(10): 2316–2322.
[16] ZHENG Xiaozhong, FENG Yanglian, MO Fang, et al. Study on effects of dietary long-chain fatty acid calcium on rumen fermentation and nutrient digestibility in beef cattle[J]. Chinese Journal of Animal Nutrition, 1999, 11(Suppl.): 157–163.
[17] XING Zhuang, ZHANG Wei, MO Fang, et al. Effects of rumen-protected fat intake on nutrient digestion, nitrogen deposition and purine derivative excretion in beef cattle[J]. Chinese Agricultural Science Bulletin, 2008, 24(3): 24–29.
[18] WU Shufeng, YANG Wenqiang, ZHANG Shuanlin, et al. Effects of protein and rumen-protected fat on rumen fermentation and urinary purine derivatives in Jinnan cattle[J]. Journal of Nuclear Agricultural Sciences, 2017, 31(7): 1436–1442.
[19] YANG Zhiling, ZHANG Rui, ZHANG Shuanlin, et al. Effects of rumen-protected fat on nutrient apparent digestibility and nitrogen deposition in Jinnan cattle[J]. Journal of Nuclear Agricultural Sciences, 2018, 32(4): 809–816.
[20] FENG Yanglian. Nutrient Requirements and Feeding Standards for Beef Cattle[M]. Beijing: China Agricultural University Press, 2000: 23.
[21] VAN SOEST P J, ROBERTSON J B, LEWIS B A. Methods for dietary fiber, neutral detergent fiber and non-starch polysaccharides relation animal nutrition[J]. Journal Dairy Science, 1991, 74(10): 3583–3597.
[22] SUN Qun. Lipid oxidation in meat products: determination of aldehydes by thiobarbituric acid test[J]. Food Science, 2002, 23(8): 331–331.
[23] MANGRUM K S, TUTTLE G, DUCKETT S K, et al. The effect of supplementing rumen undegradable unsaturated fatty acids on marbling in early-weaned steers[J]. Journal of Animal Science, 2016, 94(2): 833.
[24] ZHAO Guangyong. Ruminant Nutrition[M]. Beijing: China Agricultural University Press, 2012: 10–20.
[25] MO Fang. Cattle Production Science[M]. 2nd ed. Beijing: China Agricultural University Press, 2010: 12–42.
[26] ZAN Linsen. Cattle Production Science[M]. 2nd ed. Beijing: China Agriculture Press, 2007: 27–39.
[27] WANG Chengzhang, WANG Tian. Feed Science[M]. Beijing: China Agriculture Press, 2003: 334–338.
[28] JI Cheng. Animal Nutrition[M]. Beijing: Higher Education Press, 2008:

77-86.
[29] ZHOU Shunwu. Animal Biochemistry[M]. Beijing: Chemical Industry Press, 2008: 148-149.
[30] ZHANG Xiaotu, DU Chenhong, DING Xiaojuan, et al. Biological functions of polyunsaturated fatty acids and their application in animal production[J]. Chinese Journal of Animal Nutrition, 2017, 29(9): 3059-3067.
[31] SIEMS W G, GRUNE T, ESTERBAUER H. 4-Hydroxynonenal formation during ischemia and reperfusion of rat small intestine[J]. Life Sciences, 1995, 57(8): 785-789.
[32] HALLIWELL B, CHIRICOS S. Lipid peroxidation: its mechanism, measurement, and significance[J]. The American Journal of Clinical Nutrition, 1993, 57(Suppl.5): 715S-725S.
[33] LADEIRA M M, SANTAROSA L C, CHIZZOTTI M L, et al. Fatty acid profile, color and lipid oxidation of meat from young bulls fed ground soybean or rumen protected fat with or without monensin[J]. Meat Science, 2014, 96(1): 597-605.

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