

Research Article

Relationships of Fatty Acid Compositions with Meat Quality Traits in Hanwoo Steers

DongKyu Lee¹, Ha-Seung Seong¹, Chang-Gwon Dang¹, Sang-min Lee¹, Jaeboem Cha¹, Eun-Ho Kim¹, Joon-Ki Hong¹, Woncheoul Park¹, Jongan Lee¹, Haesu Ko¹, Aera Jang², Chungil Cho³, Mina Park^{1*}

¹ Animal Genetics & Breeding Division, National Institute of Animal Science, Cheonan-si 31000, Korea, Republic of

² Department of Applied Animal Science, College of Animal Life Sciences, Kangwon National University, Chuncheon 24341, Korea, Republic of

³ Hanwoo Genetic Improvement Center, National Agricultural Cooperative Federation Agribusiness Group Inc, Seosan 31948, Korea, Republic of

*Corresponding author: mina0412@korea.kr

ABSTRACT

This study investigated the relationships between fatty acid composition and meat quality traits in Hanwoo steers for genetic improvement. A total of 872 Hanwoo steers, raised under standardized feeding conditions, were evaluated at 24 months of age as part of the 2023–2024 national progeny testing program. Key traits analyzed included marbling score, crude fat content, shear force, and tissue texture. Fatty acid profiles comprised saturated fatty acids (myristic, palmitic, and stearic), monounsaturated fatty acids (oleic, palmitoleic, eicosenoic, and vaccenic), and polyunsaturated fatty acids (linoleic, γ -linolenic, linolenic, arachidonic, and docosatetraenoic). Kendall's tau-b correlation and path analysis were conducted to evaluate their relationships with meat quality traits. Higher marbling scores were associated with higher crude fat content and lower shear force and texture scores. Oleic, palmitic, and stearic acids accounted for $45.81 \pm 2.73\%$, $29.31 \pm 1.90\%$, and $11.14 \pm 1.50\%$ of total fatty acids, respectively. Oleic acid was correlated with lower shear force and texture values, suggesting a positive role in meat tenderness. Arachidonic acid was negatively associated with marbling score (-0.57) and crude fat (-0.65), but positively associated with shear force (0.49) and texture (0.41), indicating leaner but less tender meat. The direct effect of crude fat on marbling score showed a path coefficient of 0.52 . These results indicate that oleic acid may be a key factor for enhancing marbling and tenderness, while arachidonic acid may contribute to balancing fat deposition and texture in Hanwoo beef.

Keywords: Correlation, Fatty Acid, Hanwoo Steers, Marbling Score, Meat Quality

INTRODUCTION

The Hanwoo industry has historically focused on improving quantitative traits like carcass weight, supported by high genetic correlations among grilling cuts (Lim et al., 2016). However, simple feed supplementation shows limited effect on improving intramuscular fat due to competition with imported meat (J, 2024). Japanese Wagyu, with 78% premium market share in 2023 (Inoue et al., 2017), demonstrates successful quality differentiation via fatty acid profiling. Hanwoo, despite its superior intramuscular fat and MUFA content exceeding 50% (Kim et al., 2018; Lee et al., 2019), is still early in genetic improvement considering correlations with shear force (Moon et al., 2007). Fatty acid composition crucially determines meat quality and nutritional value. MUFA, particularly oleic acid, enhances flavor and tenderness (Chaturvedi et al., 2023). Hanwoo's high MUFA content ($52.3 \pm 3.1\%$) significantly contributes to its quality (Bhuiyan et al., 2018). Recent studies suggest arachidonic acid may increase oleic acid through metabolic pathways (Rodriguez et al., 2024). Consumer preference for health-related meat traits rose from 34% to

61% over three years (Abebe et al., 2024), emphasizing a need for quality evaluation systems reflecting Hanwoo's unique fatty acid profile (Park et al., 2010). This study aims to identify multivariate interactions between composition and content of intramuscular fat to establish breeding strategies that balance consumer preference and health functionality. Marbling score is hypothesized to be positively associated with oleic acid, influencing meat quality through metabolic regulation pathways. Identifying target fatty acids will support genetic improvement for maintaining Hanwoo's premium market position.

MATERIALS AND METHODS

Animals

This study analyzed data from 872 Hanwoo steers, 24 months of age, collected through a national progeny evaluation program between 2023 and 2024. All traits were recorded for all animals. Animals were raised under standardized feeding conditions to minimize environmental variation. Post-slaughter, *longissimus dorsi* muscle samples at the 13th thoracic vertebra was collected for fatty acid analysis.

Assessment of marbling score and tissue texture

Marbling score and meat texture are critical indicators of beef quality, affecting flavor and overall value. Carcasses were chilled to below 5°C internally and dissected. Meat surfaces were exposed to air for 10 minutes to enhance assessment. Marbling score was evaluated on a 1–9 scale using ultrasound images of the *longissimus dorsi* muscle, with intramuscular fat distribution assessed by brightness in the images. Meat texture was visually scored from 1 (best quality) to 5, based on elasticity, firmness, and surface glossiness.

Nutritional composition

Moisture, crude fat, ash, and protein contents were measured using AOAC methods (Cunniff, 1995). Moisture was determined by drying at 105°C, crude fat was extracted via Soxhlet with diethyl ether, ash was obtained by burning samples at 550°C, and protein was calculated from nitrogen content using the Kjeldahl method.

Shear Force test

Shear force of Hanwoo loin was measured following the protocol described in Jung et al. (2025). It was quantitatively analyzed on cooked samples using a Lloyd Instruments TA 1 texture analyzer with a V-shaped blade, applying a 500N load and 50 mm/min crosshead speed.

Fatty acid composition analysis

Fatty acid composition was analyzed using the method described in (Jung et al., 2024). Initially, 3 g of *longissimus dorsi* tissues underwent homogenization in 15 mL Folch solution (chloroform: methanol, 2:1 v/v) (Folch et al., 1957). After phase separation and lipid extraction, methylation was performed with NaOH-methanol and BF₃-methanol. The resulting fatty acid methyl esters were analyzed by gas chromatography using an Agilent 7890N system with an Omegawax 250 column, helium carrier gas, and flame ionization detection. The oven temperature was programmed from 150°C to 220°C with a split ratio of 100:1. PUFA No. 2-Animal Source (Supelco) was used as the reference standard.

Statistical methods

All data are presented as mean $\pm$ standard error (SE). Statistical analyses were conducted using SAS 9.4 (Institute, 1999), with significance evaluated at 5% using Duncan's multiple range test (Duncan, 1955).

Correlation Analysis (Kendall's Tau-b)

Due to non-normality of fatty acid percentage data, Kendall's Tau-b, a non-parametric method robust to outliers (Dehling et al., 2017), was used to assess pairwise relationships between fatty acids and meat quality traits. The Kendall's Tau-b coefficient is calculated as follows:

$$\tau_b = \frac{(C-D)}{\sqrt{(C+D+Tx)(C+D+Ty)}}$$

C: Number of concordant pairs (e.g., pairs where fatty acid and meat quality trait rankings align).

D: Number of discordant pairs (e.g., pairs where fatty acid and meat quality trait rankings differ).

T_x : Number of tied pairs in the fatty acid variable.

T_y : Number of tied pairs in the meat quality trait variable.

The coefficient ranges from -1 to 1 , with values closer to 1 indicating a strong positive correlation and values closer to -1 indicating a strong negative correlation.

Multivariate Regression Analysis

Multivariate regression modeled relationships between meat quality traits (dependent variables: marbling score, crude fat, shear force, texture) and fatty acid predictors (independent variables) (Breiman and Friedman, 1997; Saraiva et al., 2015). The multivariate regression model is expressed as:

$$\mathbf{Y} = \mathbf{XB} + \mathbf{E}$$

where:

$\mathbf{Y}$: $n \times 4$ matrix, where n is the number of observations (872 Hanwoo steers) and 4 represents the dependent variables (marbling score, crude fat, shear force, tissue texture).

$\mathbf{X}$: $n \times (k + 1)$ matrix, where k is the number of fatty acid predictors (12 in this study) and 1 accounts for the intercept.

$\mathbf{B}$: $(k + 1) \times 4$ matrix of regression coefficients, representing the effect of each fatty acid on the meat quality traits.

$\mathbf{E}$: $n \times 4$ matrix of error terms.

This approach accounts for inter-correlations among dependent variables while estimating fatty acid effects.

Path Analysis

Path analysis, implemented via SAS PROC CALIS, examined direct and indirect effects between fatty acids and meat quality traits to inform breeding strategies (Inoue et al., 2017; Leal-Gutiérrez et al., 2018). The path model is defined as:

$$\mathbf{y} = \mathbf{B}\mathbf{y} + \mathbf{\Gamma}\mathbf{x} + \boldsymbol{\zeta}$$

where:

$\mathbf{y}$: Vector of endogenous variables (e.g., marbling score, crude fat, shear force, tissue texture).

$\mathbf{x}$: Vector of exogenous variables (e.g., oleic acid, stearic acid, and other fatty acids).

$\mathbf{B}$: Matrix of path coefficients among endogenous variables (e.g., the effect of crude fat on marbling score).

$\mathbf{\Gamma}$: Matrix of path coefficients from exogenous to endogenous variables (e.g., the effect of oleic acid on tissue texture).

$\boldsymbol{\zeta}$: Vector of error terms.

The hypothesized path model specified that the 12 fatty acids (exogenous variables) had direct effects on the four meat quality traits (endogenous variables). Path coefficients were estimated using the Maximum Likelihood (ML) method. Model fit was evaluated by RMSEA, with values <0.08 considered acceptable (Kline, 2023; Yuan and Bentler 2007). Significant pathways, such as oleic acid's indirect effects on marbling through crude fat, were identified for quality management insights.

RESULTS AND DISCUSSION

Descriptive statistics

Table 1 presents descriptive statistics for fatty acid compositions and carcass quality traits of Hanwoo steers (n=872). Monounsaturated fatty acids (MUFA) predominated, with oleic acid highest at $45.81 \pm 2.73\%$. Saturated fatty acids (SFA), mainly palmitic ($29.31 \pm 1.90\%$) and stearic acids ($11.14 \pm 1.50\%$), were next most abundant. Polyunsaturated fatty acids (PUFA) were low at $2.40 \pm 0.50\%$, led by linoleic acid ($1.90 \pm 0.39\%$). These results agree with Bhuiyan et al. (2018), who reported similar values for oleic acid ($44.96 \pm 0.32\%$), palmitic acid ($27.02 \pm 0.19\%$), and stearic acid ($11.03 \pm 0.17\%$) in Hanwoo beef, with oleic acid about 0.85% lower than in this study. Both sets of findings support the principle of breed-specific lipid partitioning, where MUFA consistently exceed SFA (Bai et al., 2023). Stearoyl-CoA desaturase (SCD), the enzyme converting SFA to MUFA, underlies the high MUFA ratio and oleic acid content in Hanwoo (Lee et al., 2004). Conversely, PUFA proportions in Hanwoo were lower compared to Angus or Wagyu, potentially enhancing oxidative stability and storage properties (Choi et al., 2008).

Table 1. Basic statistics of fatty acid compositions and carcass quality traits in Hanwoo steers (n= 872)

Traits	Mean $\pm$ SE ¹	Minimum	Maximum	CV (%)
Carcass quality traits				
Crude fat (CF, %)	14.93 ± 4.43	4.81	35.82	29.71
Marbling score (MS, range)	4.57 ± 1.53	1	9	33.55
Tenderness/Shear force (SF, kgf) ²	6.05 ± 1.44	2.32	11.80	23.79
Tissue	1.97 ± 0.58	1	5	29.30
Fatty acids				
Saturated Fatty acid (SFA)	44.00 ± 3.00	35.00	62.00	6.21
Myristic acid (C14:0)	3.88 ± 0.61	2.23	6.37	13.51
Palmitic acid (C16:0)	29.31 ± 1.90	21.72	40.86	6.50
Stearic acid (C18:0)	11.14 ± 1.50	6.03	18.22	15.75
Mono-unsaturated fatty acid (MUFA)	53.0 ± 3.00	36.00	63.00	5.18
Palmitoleic acid (C16:1)	4.67 ± 0.77	1.65	7.22	16.55
Oleic acid (C18:1, n-9)	45.81 ± 2.73	25.07	54.90	5.97
Eicosenoic acid (C20:1)	0.14 ± 0.06	0.01	0.91	41.74
Vaccenic acid (C18:1, n-7)	2.61 ± 1.00	0.18	6.80	38.27
Poly-unsaturated fatty acid (PUFA)	2.40 ± 0.50	1.10	5.80	19.43
Linolenic acid (C18:3, n-3)	0.10 ± 0.03	0.01	0.25	20.33
γ -Linolenic acid (C18:3, n-6)	0.04 ± 0.03	0.00	0.19	63.34
Linoleic acid (C18:2, n-6)	1.90 ± 0.39	0.63	4.40	27.85
Arachidonic acid (C20:4, n-6)	0.32 ± 0.11	0.06	1.12	35.68
Docosatetraenoic acid (C22:4, n-6)	0.09 ± 0.05	0.00	1.01	48.41

¹ SE, standard error of the mean.

² Shear force was measured in the *Longissimus thoracis*.

Correlation between fatty acid compositions and meat quality traits

Table 2 shows Kendall's tau-b correlation coefficients between fatty acid compositions and carcass quality traits in Hanwoo steers ($n = 872$). Kendall's tau-b, a non-parametric method robust to outliers and skewed data, was used to evaluate associations (Dehling et al., 2017). Findings indicated that PUFA negatively correlated with marbling score (MS) and crude fat (CF), with arachidonic acid showing strong negative correlations (MS: -0.567, CF: -0.651), suggesting inhibitory effects on fat deposition consistent with findings in Brangus breed (Rodriguez et al., 2024). Conversely, arachidonic acid positively correlated with shear force (SF: 0.493) and tissue texture (0.413), indicating influence on meat physical properties. Among SFA, myristic acid was positively correlated with MS (0.126) and CF (0.148) but negatively with SF (-0.158) and tissue texture (-0.088). Palmitic and stearic acids showed weak correlations, though stearic acid may promote tenderness (Bai et al., 2023; Dos Santos et al., 2022). For MUFA, Vaccenic acid was positively correlated with SF (0.103) and tissue texture (0.085), highlighting MUFA-PUFA interaction effects observed in breed-specific studies (Feitosa et al., 2017; Otto et al., 2024). While Kendall's tau-b effectively identified pairwise associations, it cannot capture complex interactions among variables; thus, multivariate regression was performed for comprehensive analysis.

Table 2. Kendall's tau-b correlation coefficients between fatty acid composition and carcass quality traits in Hanwoo steers ($n = 872$)

Fatty acid	MS	CF	SF	Tissue
Saturated fatty acid				
Myristic acid	0.126***	0.148***	-0.158***	-0.088**
Palmitic acid	0.048	0.020	-0.081***	-0.025
Stearic acid	-0.046	-0.001	-0.011	0.048
Monounsaturated fatty acid				
Oleic acid	0.033	0.01	0.038	-0.054
Palmitoleic acid	0.042	0.03	-0.041	-0.043
Eicosenoic acid	0.065*	0.049*	-0.011	-0.070*
Vaccenic acid	-0.062*	-0.047	0.103***	0.085**
Polyunsaturated fatty acid				
Linoleic acid	-0.223***	-0.219***	0.179***	0.184***
γ -Linolenic acid	0.000	0.016	-0.069**	-0.028
Linolenic acid	-0.044	-0.036	0.051*	0.142***
Arachidonic acid	-0.567***	-0.651***	0.493***	0.413***
Docosatetraenoic acid	-0.235***	-0.252***	0.141***	0.161***

MS, marbling score; CF, crude fat; SF, shear force; *, significance at $P < 0.05$; **, significance at $P < 0.01$; ***, significance at $P < 0.001$.

Multivariate regression analysis

A multivariable regression model was fitted to assess the combined effects of 12 fatty acids on meat quality traits (Breiman and Friedman, 1997; Saraiva et al., 2015). The results, detailed in Table 3, revealed that arachidonic acid had the most substantial influence on the overall model, showing the highest partial coefficient of determination ($R^2 = 0.584$), which indicates its unique contribution to trait variance. Linoleic acid had the next largest effect ($R^2 = 0.133$). Specifically, higher levels of arachidonic acid were significantly associated with lower marbling scores (MS; -0.015 ± 0.003) and crude fat (CF; -0.011 ± 0.001), but with increased shear force (SF; 0.012 ± 0.003) and tissue texture (0.018 ± 0.006). Other notable effects included a negative association between stearic acid and MS (-0.257 ± 0.063) and between palmitic acid and both CF (-0.118 ± 0.029) and SF (-0.363 ± 0.077). Conversely, oleic acid positively affected shear force (0.380 ± 0.111) while negatively influencing tissue texture (-0.462 ± 0.225). These findings underscore the dominant and complex role of arachidonic acid in determining

Hanwoo meat quality. While multivariate regression isolates individual fatty acid effects, it does not capture indirect or interaction effects, motivating further path analysis (Alves et al., 2019; Puvača et al., 2014). Such approaches have been applied in livestock fatty acid research to better understand trait relationships (Harnly et al., 2022).

Table 3. Multivariate regression analysis of fatty acid composition in relation to carcass traits of Hanwoo cattle

Fatty acid	R ²	MS ± SE	CF ± SE	SF ± SE	Tissue ± SE
Myristic acid	0.061	0.015 ± 0.025	0.010 ± 0.009	-0.078 ± 0.024**	0.058 ± 0.049
Palmitic acid	0.036	0.136 ± 0.079	-0.118 ± 0.029***	-0.363 ± 0.077***	0.113 ± 0.156
Stearic acid	0.029	-0.257 ± 0.063***	0.046 ± 0.023*	-0.078 ± 0.061	0.033 ± 0.124
Oleic acid	0.024	0.104 ± 0.114	0.057 ± 0.042	0.380 ± 0.111**	-0.462 ± 0.225*
Palmitoleic acid	0.012	0.049 ± 0.033	-0.017 ± 0.012	-0.048 ± 0.032	-0.015 ± 0.064
Eicosenoic acid	0.023	0.002 ± 0.002	0.003 ± 0.001**	0.006 ± 0.002*	-0.001 ± 0.005
Vaccenic acid	0.030	-0.003 ± 0.042	0.040 ± 0.015**	0.146 ± 0.040***	0.173 ± 0.082*
Linoleic acid	0.133	-0.025 ± 0.015	-0.011 ± 0.006	0.025 ± 0.015	0.073 ± 0.030*
r-Linolenic acid	0.021	-0.003 ± 0.001**	0.000 ± 0.000	-0.003 ± 0.001**	-0.005 ± 0.002*
Linolenic acid	0.060	0.001 ± 0.001	0.001 ± 0.000**	0.003 ± 0.001*	0.012 ± 0.002***
Arachidonic acid	0.584	-0.015 ± 0.003***	-0.011 ± 0.001***	0.012 ± 0.003***	0.018 ± 0.006**
Docosatetraenoic acid	0.034	-0.003 ± 0.002	-0.001 ± 0.001	-0.001 ± 0.002	0.004 ± 0.004

R²; Partial regression coefficient, MS, marbling score; CF, crude fat; SF, shear force; SE, standard error; *, significance at P<0.05; **, significance at P<0.01; ***, significance at P<0.001.

Path analysis between fatty acid and meat quality traits

Path analysis reveals complex relationships between fatty acid profiles and meat quality in Hanwoo steers (Inoue et al., 2017; Leal-Gutiérrez et al., 2018; Pegolo et al., 2020). The hypothesized path model provided a reasonable approximation of the relationships within the data. The model fit indices (CFI = 0.891; TLI = 0.874; RMSEA = 0.079) indicate that while the model does not perfectly capture all the variance, it offers a statistically useful interpretation of the causal pathways between fatty acids and meat quality traits. Table 4 summarizes path coefficients showing how fatty acids affect MS, CF, SF, and tissue texture. Among SFA, myristic acid significantly increased MS (0.234 ± 0.049) and CF (0.404 ± 0.048), whereas palmitic acid decreased CF (-0.266 ± 0.048). Among MUFA, palmitoleic acid and eicosenoic acid increased intramuscular fat content, while vaccenic acid increased SF (0.159 ± 0.037) and tissue texture (0.126 ± 0.037). PUFA showed contrasting effects; notably, arachidonic acid strongly reduced MS (-0.686 ± 0.032) and CF (-0.753 ± 0.029), yet increased SF (0.675 ± 0.033) and tissue texture (0.512 ± 0.037), indicating its role in strengthening meat structure (Inoue et al., 2017; Leal-Gutiérrez et al., 2018). Further path analysis explored interactions among SFA, MUFA, and PUFA, and their direct and indirect effects on fatty acid metabolism and distribution, enhancing understanding of the multifaceted influence of fatty acids on meat quality traits.

Implications of the relationships between marbling score and fatty acid composition

This study systematically analyzed the relationship between intramuscular fat composition and MS in Hanwoo steers. Among PUFA, arachidonic acid negatively affected MS and CF but positively influenced SF and texture, confirming its key role in Hanwoo meat quality. In contrast, oleic acid (mean $45.81 \pm 2.73\%$) among MUFA enhanced beef palatability and softness (Farmer and Farrell, 2018; Vela-Vásquez et al., 2022). Myristic acid, a SFA, raised MS and CF, suggesting an indirect role in meat quality via PUFA interactions (Falowo et al., 2017). Breed differences show Hanwoo has higher MUFA and greater tenderness compared to Wagyu and Angus, with Wagyu excelling in marbling and flavor (Inoue et al., 2017) and Angus valued for growth rate and uniform quality (Duff et al., 2022). Hanwoo's traits reflect genetics and selective breeding, highlighting fatty acid and meat quality interplay (Lim et al., 2016). Although PUFA constitutes only 3-5% of total fatty acids, it may improve meat quality through interactions with SFA and MUFA (Otto et al., 2022). However, excessive PUFA may cause

Table 4. Path analysis estimates of the relationships among fatty acids and carcass quality traits in Hanwoo steers (n = 872)

Fatty acid	MS $\pm$ SE	CF $\pm$ SE	SF $\pm$ SE	Tissue $\pm$ SE
Saturated fatty acid(SFA)				
Myristic acid	0.234 $\pm$ 0.049***	0.404 $\pm$ 0.048***	-0.309 $\pm$ 0.049***	-0.130 $\pm$ 0.050**
Palmitic acid	-0.096 $\pm$ 0.049*	-0.266 $\pm$ 0.048***	0.090 $\pm$ 0.048*	0.063 $\pm$ 0.049
Stearic acid	-0.070 $\pm$ 0.037*	0.064 $\pm$ 0.036*	-0.057 $\pm$ 0.037	0.048 $\pm$ 0.038
Monounsaturated fatty acid(MUFA)				
Oleic acid	0.045 $\pm$ 0.040	0.002 $\pm$ 0.040	0.062 $\pm$ 0.040	-0.081 $\pm$ 0.040*
Palmitoleic acid	0.126 $\pm$ 0.038***	0.074 $\pm$ 0.038*	-0.105 $\pm$ 0.038**	-0.115 $\pm$ 0.038**
Eicosenoic acid	0.100 $\pm$ 0.038**	0.127 $\pm$ 0.039***	-0.075 $\pm$ 0.038*	-0.060 $\pm$ 0.038
Vaccenic acid	-0.099 $\pm$ 0.037**	-0.067 $\pm$ 0.037*	0.159 $\pm$ 0.037***	0.126 $\pm$ 0.037***
Polyunsaturated fatty acid(PUFA)				
Linoleic acid	-0.006 $\pm$ 0.033	-0.003 $\pm$ 0.031	-0.020 $\pm$ 0.034	-0.025 $\pm$ 0.038
γ -linolenic acid	0.008 $\pm$ 0.029	0.050 $\pm$ 0.026*	-0.100 $\pm$ 0.029***	-0.095 $\pm$ 0.033**
Linolenic acid	0.004 $\pm$ 0.030	0.062 $\pm$ 0.027*	0.034 $\pm$ 0.030	0.163 $\pm$ 0.034***
Arachidonic acid	-0.686 $\pm$ 0.032***	-0.753 $\pm$ 0.029***	0.675 $\pm$ 0.033***	0.512 $\pm$ 0.037***
Docosatetraenoic acid	0.031 $\pm$ 0.030	0.041 $\pm$ 0.028	-0.047 $\pm$ 0.031	-0.003 $\pm$ 0.034

MS, marbling score; CF, crude fat; SF, shear force; SE, standard error; *, significance at $P < 0.05$; **, significance at $P < 0.01$; ***, significance at $P < 0.001$.

oxidative instability, reducing taste (Falowo et al., 2017). Therefore, selectively reducing PUFA and increasing MUFA can improve both nutritional value and consumer preference (Zhang et al., 2017). Oleic acid shows high genetic variability (CV 5.97%) and a normal distribution, promising for quality improvement, a potential supported by component analyses in other livestock such as pork (Kim et al., 2018). Subsequent research should estimate heritability via REML and breeding values by BLUP to evaluate fatty acid and meat quality relationships accurately (Lee et al., 2019; Zhang et al., 2017).

CONCLUSIONS

This study analyzed multivariate relationships between fatty acid compositions and meat quality traits of Hanwoo steers using advanced statistical modeling. Arachidonic acid was consistently associated with reduced marbling ($\tau = -0.567$) and crude fat, but positively correlated with shear force ($\tau = 0.493$) and texture, indicating a trade-off between fat deposition and tenderness. These findings suggest that arachidonic acid plays a dual role in metabolic regulation and the determination of meat quality. Oleic acid was not significantly correlated with marbling score in initial analyses, yet regression results indicated a positive coefficient with shear force ($\beta = 0.380$), implying an increase in shear force values. Since higher shear force reflects reduced tenderness, this finding suggests that oleic acid may indirectly influence palatability in a complex manner rather than uniformly improving meat quality. Taken together, these findings highlight the importance of metabolic pathways associated with fatty acid interactions, particularly the conversion of saturated fatty acids (SFA) to monounsaturated fatty acids (MUFA). While arachidonic acid, as a polyunsaturated fatty acid (PUFA), appears to affect fat deposition and toughness, oleic acid, as a predominant MUFA, may still play a role in modulating flavor and overall palatability under specific conditions. From a breeding perspective, strategies aimed at enhancing oleic acid content while also managing excessive arachidonic acid levels. This approach could provide a more balanced approach to improving both tenderness and intramuscular fat characteristics, thereby contributing to the economic value of Hanwoo beef. Overall, this study provides a systematic framework for evaluating the complex associations between fatty acid composition and beef quality traits. The findings offer essential baseline information for developing more precise genetic and management strategies that balance fat deposition, tenderness, and flavor in Hanwoo beef.

ACKNOWLEDGEMENTS

This study was supported by the Cooperative Research Program (Project No. PJ01670307) and the RDA Research Associate Fellowship Program of the National Institute of Animal Science, Rural Development Administration, Republic of Korea.

REFERENCES

- Abebe BK, Wang J, Guo J, Wang H, Li A, Zan L. 2024. A review of emerging technologies, nutritional practices, and management strategies to improve intramuscular fat composition in beef cattle. *Animal Biotechnology* 35:2388704.
- Alves AaC, Pinzon AC, Da Costa RM, Da Silva MS, Vieira EHM, De Mendonca IB, Viana VDSS, Lôbo RNB. 2019. Multiple regression and machine learning based methods for carcass traits and saleable meat cuts prediction using non-invasive in vivo measurements in commercial lambs. *Small Ruminant Research* 171:49-56.
- Bai H, Zhang M, Zhao Y, Wang R, Zhang G, Lambo MT, Zhang Y, Li Y, Wang L. 2023. Altering the ratio of palmitic, stearic, and oleic acids in dietary fat affects nutrient digestibility, plasma metabolites, growth performance, carcass, meat quality, and lipid metabolism gene expression of angus bulls. *Meat Science* 199:109138.
- Bhuiyan M, Lee D, Kim H, Lee S, Cho S, Yang B, Kim S. 2018. Estimates of genetic parameters for fatty acid compositions in the longissimus dorsi muscle of hanwoo cattle. *animal* 12:675-683.
- Breiman L, Friedman JH. 1997. Predicting multivariate responses in multiple linear regression. *Journal of the Royal Statistical Society Series B: Statistical Methodology* 59:3-54.
- Chaturvedi D, Bharti D, Dhal S, Sahu D, Behera H, Sahoo M, Kim D, Jarzębski M, Anis A, Mohanty B. 2023. Role of stearic acid as the crystal habit modifier in candelilla wax-groundnut oil oleogels. *ChemEngineering* 7:96.
- Choi C-B, Shin H-U, Lee S-O, Kim S-I, Jung K-K, Choi C-W, Baek K-H, Lunt DK, Smith SB. 2008. Comparison of cholesterol contents and fatty acid composition in m. Longissimus of hanwoo, angus and wagyu crossbred steers. *Journal of Animal Science and Technology* 50:519-526.
- Cunniff P. 1995. *AOAC international. Official Methods of Analysis of AOAC International*.
- Dehling H, Vogel D, Wendler M, Wied D. 2017. Testing for changes in kendall's tau. *Econometric Theory* 33:1352-1386.
- Dos Santos NJ, Bezerra LR, Castro DP, Marcelino PD, Virginio Júnior GF, Da Silva Júnior JM, Pereira ES, De Andrade EA, Silva TM, Barbosa AM. 2022. Effect of dietary palm kernel oil on the quality, fatty acid profile, and sensorial attributes of young bull meat. *Foods* 11:609.
- Duff C, Samaraweera A, McGilchrist P, Clark S. Genetic parameters for fatty acid traits of beef in australian angus. *Proceedings of 12th World Congress on Genetics Applied to Livestock Production (WCGALP)*. p[^]pp.
- Duncan DB. 1955. Multiple range and multiple f tests. *biometrics* 11:1-42.
- Falowo AB, Muchenje V, Hugo A. 2017. Effect of sous-vide technique on fatty acid and mineral compositions of beef and liver from bonsmara and non-descript cattle. *Annals of Animal Science* 17:565.
- Farmer L, Farrell D. 2018. Beef-eating quality: A european journey. *Animal* 12:2424-2433.
- Feitosa FLB, Olivieri BF, Aboujaoude C, Pereira ASC, De Lemos MVA, Chiaia HLJ, Berton MP, Peripolli E, Ferrinho AM, Mueller LF. 2017. Genetic correlation estimates between beef fatty acid profile with meat and carcass traits in nellore cattle finished in feedlot. *Journal of Applied Genetics* 58:123-132.
- Folch J, Lees M, Stanley GS. 1957. A simple method for the isolation and purification of total lipides from animal tissues. *Journal of biological chemistry* 226:497-509.
- Gamarra D, Aldai N, Arakawa A, Barron LJR, López-Oceja A, De Pancorbo MM, Taniguchi M. 2018. Distinct correlations between lipogenic gene expression and fatty acid composition of subcutaneous fat among cattle breeds. *BMC veterinary research* 14:1-12.
- Harnly J, Picklo MJ, Kalscheur KF, Magnuson A, Bukowski MR, Fukagawa NK, Finley JW. 2022. Deriving information from complex data sets: Impact of forage on fatty acids in cow milk. *Journal of Food Composition and Analysis* 107:104179.
- Hwang Y-H, Joo S-T. 2017. Fatty acid profiles, meat quality, and sensory palatability of grain-fed and grass-fed beef from hanwoo, american, and australian crossbred cattle. *Korean journal for food science of animal resources* 37:153.
- Inoue K, Shoji N, Honda T, Oyama K. 2017. Genetic relationships between meat quality traits and fatty acid composition in japanese black cattle. *Animal Science Journal* 88:11-18.

- Institute SaS. 1999. Sas/stat user's guide. SAS Publ.
- J K. 2024. Korean beef farmers rally at national assembly for the first time in 12 years. 2024.07.04.
- Jung Y, Oh S, Kim D, Lee S, Lee H-J, Shin D-J, Choo H-J, Jo C, Nam K-C, Lee J-H. 2024. Effect of cinnamon powder on quality attributes and off-flavor in fried chicken drumsticks made from long-term thawed korean native chicken. *Poultry Science* 103:103583.
- Jung Y, Oh S, Lee S, Lee H-J, Choo H-J, Jo C, Nam K-C, Lee J-H, Jang A. 2025. Characterization of meat quality, storage stability, flavor-related compounds, and their relationship in korean woorimatdag no. 2 chicken breast meat during cold storage. *Poultry Science* 104:104566.
- Kim TW, Kim CW, Noh CW, Kim SW, Kim I-S. 2018. Identification of association between supply of pork and production of meat products in korea by canonical correlation analysis. *Korean journal for food science of animal resources* 38:794.
- Kline RB. 2023. Principles and practice of structural equation modeling. Guilford publications.
- Leal-Gutiérrez JD, Rezende FM, Elzo MA, Johnson D, Peñagaricano F, Mateescu RG. 2018. Structural equation modeling and whole-genome scans uncover chromosome regions and enriched pathways for carcass and meat quality in beef. *Frontiers in genetics* 9:532.
- Lee S-H, Kim C-N, Ko K-B, Park S-P, Kim H-K, Kim J-M, Ryu Y-C. 2019. Comparisons of beef fatty acid and amino acid characteristics between jeju black cattle, hanwoo, and wagyu breeds. *Food science of animal resources* 39:402.
- Lee S, Yoon D, Hwang S, Cheong E, Kim O, Lee C. 2004. Relationship between monounsaturated fatty acid composition and stearoyl-coa desaturase mrna level in hanwoo liver and loin muscle. *Journal of Animal Science and Technology* 46:7-14.
- Lim D, Strucken EM, Choi BH, Chai HH, Cho YM, Jang GW, Kim T-H, Gondro C, Lee SH. 2016. Genomic footprints in selected and unselected beef cattle breeds in korea. *PloS one* 11:e0151324.
- Moon W, Kim B, Roh S, Kim H, Jung D, Sun D, Kim K, Yoon Y, Jung J, Jeon J. 2007. Estimation of environmental effect and genetic parameters for the carcass traits in hanwoo (korean cattle). *Journal of Animal Science and Technology* 49:689-698.
- Otto JR, Mwangi FW, Pewan SB, Adegboye OA, Malau-Aduli AE. 2022. Lipogenic gene single nucleotide polymorphic DNA markers associated with intramuscular fat, fat melting point, and health-beneficial omega-3 long-chain polyunsaturated fatty acids in australian pasture-based bowen genetics forest pastoral angus, hereford, and wagyu beef cattle. *Genes* 13:1411.
- Otto JR, Mwangi FW, Pewan SB, Adegboye OA, Malau-Aduli AEO. 2024. Correction: Muscle biopsy long-chain omega-3 polyunsaturated fatty acid compositions, imf and fmp in australian pasture-based bowen genetics forest pastoral angus, hereford, and wagyu beef cattle. *BMC Veterinary Research* 20:452.
- Park BK, Choi N-J, Kim HC, Kim TI, Cho YM, Oh YK, Im SK, Kim YJ, Chang JS, Hwang IH. 2010. Effects of amino acid-enriched ruminally protected fatty acids on plasma metabolites, growth performance and carcass characteristics of hanwoo steers. *Asian-Australasian journal of animal sciences* 23:1013-1021.
- Pegolo S, Momen M, Morota G, Rosa GJ, Gianola D, Bittante G, Cecchinato A. 2020. Structural equation modeling for investigating multi-trait genetic architecture of udder health in dairy cattle. *Scientific Reports* 10:7751.
- Puvača N, Lukač D, Ljubojević D, Stanačev V, Beuković M, Kostadinović L, Plavša N. 2014. Fatty acid composition and regression prediction of fatty acid concentration in edible chicken tissues. *World's Poultry Science Journal* 70:585-592.
- Rodriguez EE, Hamblen H, Leal-Gutierrez JD, Carr C, Scheffler T, Scheffler JM, Mateescu RG. 2024. Exploring the impact of fatty acid composition on carcass and meat quality in bos taurus indicus influenced cattle. *Journal of Animal Science* 102:skae306.
- Saraiva C, Oliveira I, Silva J, Martins C, Ventanas J, García C. 2015. Implementation of multivariate techniques for the selection of volatile compounds as indicators of sensory quality of raw beef. *Journal of Food Science and Technology* 52:3887-3898.
- Silva-Martínez GA, Rodríguez-Ríos D, Alvarado-Caudillo Y, Vaquero A, Esteller M, Carmona FJ, Moran S, Nielsen FC, Wickström-Lindholm M, Wrobel K. 2016. Arachidonic and oleic acid exert distinct effects on the DNA methylome. *Epigenetics* 11:321-334.
- Troy DJ, Tiwari BK, Joo S-T. 2016. Health implications of beef intramuscular fat consumption. *Korean Journal for Food Science of Animal Resources* 36:577.
- Vela-Vásquez DA, Sifuentes-Rincón AM, Delgado-Enciso I, Ordaz-Pichardo C, Arellano-Vera W, Treviño-Alvarado V. 2022. Effect of consuming beef with varying fatty acid compositions as a major source of protein in volunteers under a personalized nutritional program. *Nutrients* 14:3711.
- Yuan K-H, Bentler PM. 2007. 3. Multilevel covariance structure analysis by fitting multiple single-level models. *Sociological Methodology* 37:53-82.
- Zhang F, Ekine-Dzivenu C, Vinsky M, Basarab J, Aalhus J, Dugan M, Li C. 2017. Phenotypic and genetic relationships of residual feed intake measures and their component traits with fatty acid composition in subcutaneous adipose of beef cattle. *Journal of animal science* 95:2813-2824.