71st ICoMST
GIRONA - CATALONIA - SPAIN
3rd-8th August - 2025

DEVELOPMENT OF A NEAR-INFRARED SPECTROSCOPY DEVICE FOR ON-SITE NUTRITIONAL ASSESSMENT OF BEEF CARCASSES

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I. INTRODUCTION

Beef quality is principally determined by its nutritional composition—moisture, crude protein, crude fat—and fatty acid profile, especially oleic acid ($C_{18:1}$), which enhances juiciness and flavor. Traditional laboratory analyses (drying, Kjeldahl, Soxhlet extraction, gas chromatography) are accurate but time-consuming, destructive, and unsuitable for on-site use. Near-infrared spectroscopy (NIR) provides a rapid, non-destructive alternative for predicting multiple components in intact meat, yet existing handheld NIR probes have limited measurement areas that undermine reliability on heterogeneous carcass surfaces. To overcome this, a reflection-mode handheld NIR spectrometer (1000–1700 nm) with an enlarged 40 mm illumination window was developed for real-time nutritional assessment of Hanwoo beef carcasses in slaughterhouse environments.

II. MATERIALS AND METHODS

In this study, we developed a portable NIR system based on a Stellarnet Dwarf spectrometer (Stellarnet, Inc., Tampa, FL, USA) covering the 1000–1700 nm wavelength range. The spectrometer was integrated into a backpack-style handheld device providing a 40 mm measurement window. Optical design and ray-tracing simulations were performed in Zemax OpticStudio (Version 20, Zemax LLC, Middlefield, CT, USA). Between September and November 2024, we acquired reflectance spectra from 243 chilled beef carcasses (marbling grades 1–9) at a commercial slaughterhouse (Figure 1). For each carcass, spectra were collected directly from the chilled surface; subsamples were then taken on ice to the laboratory for reference analyses. Physicochemical determinations—moisture, crude protein, and crude fat—followed AOAC official methods, and fatty acid profiles were quantified by gas chromatography. To ensure reproducibility, six analytical replicates were performed per carcass. Prior to each measurement session, white and dark references were recorded for intensity calibration. All raw spectra underwent intensity calibration and preprocessing (e.g., scatter-correction, smoothing) before model development. Multivariate calibration models, including Partial Least Squares Regression (PLSR) and Random Forest, were constructed to predict carcass composition from the preprocessed spectra. Statistical differences among marbling grades were assessed by one-way ANOVA ($\alpha = 0.05$) followed by Duncan's multiple range test.

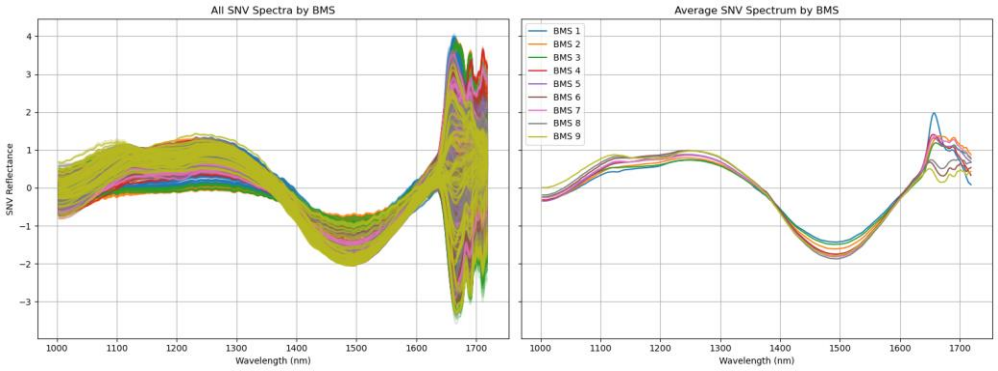


Figure 1. NIR Spectrometer System and GUI for On-Site Beef Carcass Analysis.

III. RESULTS AND DISCUSSION

As shown in Table 1, as BMS grade increased from 1 (low marbling) to 9 (high marbling), moisture content significantly decreased from 72.1 % to 54.3 % and crude protein also decreased from 22.2 % to 16.5 % (both $P < 0.001$), whereas crude fat increased from 4.5 % to 27.9 % and oleic acid content rose from 19.9 to 137.1 mg/g (both $P < 0.001$). These grade-dependent shifts underscore the close relationship between marbling score and key beef quality attributes [1].

Table 1 –Chemical composition of beef carcasses by beef marbling score(BMS) and grade.

Meat grade	1++			1+	1		2		3	SEM	*P* value
BMS grade	9	8	7	6	5	4	3	2	1		
Moisture (%)	54.3^{i}	56.2^{h}	59.4^{g}	61.4^{f}	64.3^{e}	65.6^{d}	67.9^{c}	68.7^{b}	72.1^{a}	0.19	<0.001
Crude protein (%)	16.5^{i}	17.0^{h}	17.9^{g}	18.9^{f}	19.8^{e}	20.2^{d}	20.7^{c}	21.1^{b}	22.2^{a}	0.06	<0.001
Crude fat (%)	27.9^{a}	25.5^{b}	21.4^{c}	18.3^{d}	14.5^{e}	12.9^{f}	10.1^{g}	8.8^{h}	4.5^{i}	0.25	<0.001
Oleic acid (mg/g)	137.1^{a}	122.5^{b}	102.6^{c}	86.8^{d}	69.3^{e}	60.2^{f}	47.7^{g}	41.2^{h}	19.9^{i}	1.29	<0.001

SEM: Standard error of mean

As shown in Table 2, Random Forest models consistently outperformed PLSR across all four parameters. While PLSR achieved moderate calibration R^2 values (0.67–0.74) and prediction R^2 values (0.64–0.72) with relatively high RMSEs (e.g., RMSEP up to 22.9 mg/g for oleic acid), Random Forest delivered very high calibration R^2 (> 0.98), stronger prediction R^2 (0.86–0.91), and substantially lower RMSEs in both calibration and validation. Slaughterhouse environments are characterized by high humidity and frequent carcass shaking during measurement [2]. This, along with variable muscle and fat fiber orientation, surface moisture, temperature fluctuations, ambient light interference, and measurement angle variations, can introduce complex scattering effects into the spectra. These combined nonlinear distortions suggest that a nonlinear modeling approach, such as Random Forest, is better suited to this dataset than the linear PLSR method.

Table 2 –PLSR and random forest model performance metrics for moisture, crude protein, crude fat, and oleic acid.

Parameter	Regression model	R^2_C	RMSEC	R^2_P	RMSEP
Moisture(%)	PLSR	0.74±0.01	2.98±0.04	0.72±0.01	3.11±0.09
	Random forest	0.98±0.01	0.72±0.02	0.89±0.01	1.91±0.10
Crude protein(%)	PLSR	0.70±0.01	1.04±0.01	0.67±0.02	1.09±0.02
	Random forest	0.98±0.01	0.22±0.01	0.90±0.01	0.57±0.03
Crude fat(%)	PLSR	0.74±0.01	3.86±0.05	0.72±0.01	4.04±0.11
	Random forest	0.98±0.01	0.83±0.02	0.91±0.01	2.22±0.13
Oleic acid(mg/g)	PLSR	0.67±0.01	21.79±0.53	0.64±0.02	22.91±1.13
	Random forest	0.98±0.01	5.06±0.18	0.86±0.02	13.41±1.15

PLSR: Partial least square regression; R^2_C: calibration set coefficient of determination; R^2_P: prediction set coefficient of determination; RMSEC: root mean square error of calibration set; RMSEP: root mean square error of prediction set;

IV. CONCLUSION

A reflection-mode handheld NIR spectrometer (1000–1700 nm, 40 mm illumination area) was developed for real-time, on-site assessment of Hanwoo beef carcass composition. Reflectance spectra from 243 chilled carcasses (BMS 1–9) were acquired, and both linear (PLSR) and non-linear (Random Forest) calibration models were constructed. The Random Forest model markedly outperformed PLSR, achieving calibration $R^2 > 0.98$ and prediction $R^2 \geq 0.86$ for moisture, protein, fat, and oleic acid, with substantially lower RMSE values in calibration and validation. These results demonstrate the device's ability to reliably predict key nutritional and quality attributes of beef carcasses in situ within a slaughterhouse environment.

ACKNOWLEDGEMENTS

This study was supported by Chungnam National Univeristy, Republic of Korea

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