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Online Near-Infrared Spectroscopy for the Measurement of Cow Milk Quality in an Automatic Milking System †

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Abstract: This study developed an online near-infrared spectrometer for measuring cow milk quality indicators, such as fat, protein, and lactose, solids not fat, and somatic cell count. Milk samples were obtained from 24 Holstein cows and analyzed using an automatic milking system. The system demonstrated high accuracy for predicting each's cow milk quality every 20 s during milking and at one milking time, allowing dairy farmers to improve farm management and produce high-quality milk. This precision dairy farming system could help dairy farmers overcome individual cow management issues and achieve high-quality milk production.

Keywords: near-infrared spectroscopy; milk quality; somatic cell count; dairy precision farming

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1. Introduction

Dairy farming requires many specific jobs, including milking, feeding, managing livestock, feed production and manure processing [1]. Large scale dairy farmers routinely manage their livestock in groups in a system known as herd management [1,2]. However, a system called individual cow management is needed to monitor the quality of the milk components of each cow, which is essential for breeding, efficient cow utilization and feed management. For these reasons, there is a recent need for a technology that allows dairy farmers to measure the milk quality of individual cows during milking [3,4].

The non-invasive, fast, user-friendly, time saving, and pretreatment-free features of near-infrared spectroscopy (NIRS) makes it an adequate technique for measuring milk quality during the milking process [5–9]. NIRS was used to measure and provide qualitative and quantitative information on agricultural products, including rice, wheat, pomegranate, and carrots [10–14]. NIRS has been used in practice to automatically measure rice quality in Japan [13]. However, the use of NIRS for online monitoring of individual cows in real-time during milking has not yet been realize [15,16].

In this study, an experimental online near-infrared (NIR) spectrometer for milk quality measurement was developed. According to Iweka et al., [17], the NIR spectrometer can be used to measure the milk quality of individual cow during milking in real-time with acceptable precision and accuracy. For this reason, we installed the NIR spectrometer into an automatic milking system.

The purpose of this study was to investigate the precision and accuracy of the NIR spectroscopic sensing system for individual cow milk quality measurement in an automatic milking system.

2. Materials and Methods

2.1. Near-Infrared Spectroscopy

An experimental-based online NIR spectrometer was developed to measure each cow's milk quality during milking. The set-up included a laptop computer, a milk flow meter, a milk sampler, and an NIR spectroscopy sensor (Figure 1). The NIR spectroscopic sensing system was put into an automatic milking system (GEA Farm Technologies, Bönen, Germany). The milk chamber of the NIR spectroscopy sensor was constantly filled with raw milk from the automatic milking system through a bypass. Extra raw milk was discharged into a bulk milk tank through a line tube after flowing past the milk flow meter. A milk sample occupied about 30 mL of the milk chamber of the NIR spectroscopy sensor (Table 1). The halogen lamps A and B had their optical axes set at the same level as the optical fiber, but halogen lamp C had its optical axis set 5 mm higher than the optical fiber (Figure 2). Through the milk, the NIR spectroscopy sensor collected absorbance spectra. Spectral were collected during milking at 1 nm intervals every 20 s in the 700 nm to 1050 nm wavelength range. The laptop computer concurrently recorded the milk flow rate.

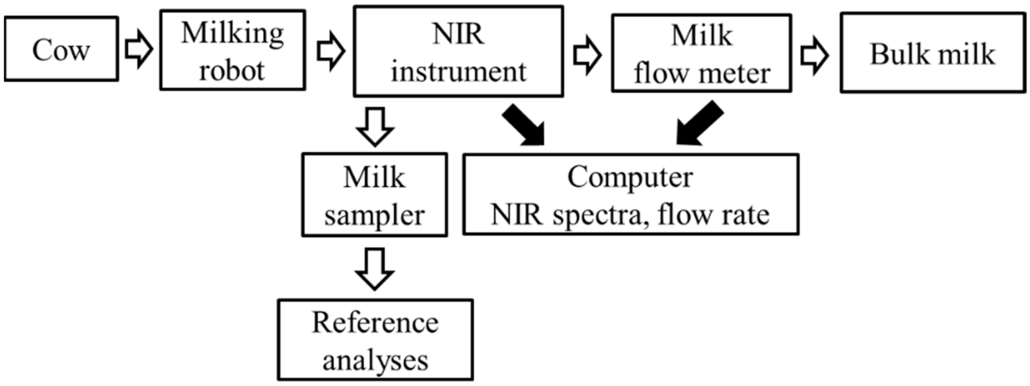

Figure 1. Flow chart of an online near-infrared spectrometer for measuring milk quality in an automatic milking system.

Table 1. Specifications of the near-infrared spectroscopy instrument.

Devices	Specifications
NIR spectrum sensor	Absorbance spectrum sensor
Light source	Three halogen lamps
Optical fiber	Quartz Fiber
Milk chamber surface	Glass
Volume of milk sample	Approx. 30 mL
Distance between optical axis and milk level	55 mm
NIR spectrometer	Diffraction grating spectrometer
Optical density	Absorbance
Wavelength range	700–1050 nm, 1-nm internal
Wavelength resolution	Approx. 6.4 nm
Photocell	CMOS linear array, 512 pixels
Thermal controller	Heater and cooling fan
Data processing computer	Windows 7
A/D converter	16 bit
Spectrum data acquisition	Every 20 s

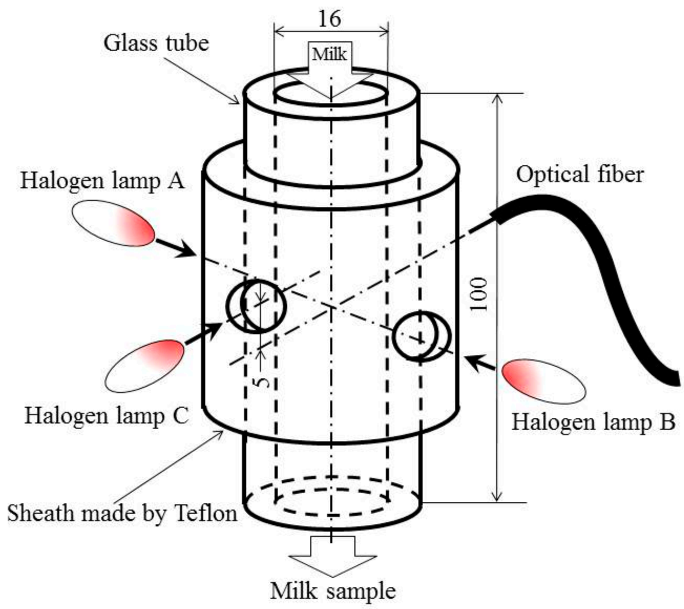

Figure 2. Schematic of the optical system of the milk chamber of the near-infrared spectroscopy sensor.

2.2. Holstein Cows and Milk Samples

In this study, we used 24 Holstein cows from a dairy barn in the Tochigi prefecture of Japan. The lactation phases of these cows varied. On 28 and 29 November 2019, which were successive days, the experiment was carried out continuously throughout the day. Once a cow entered the automatic milking system, the milking began immediately. Throughout milking, milk samples were taken from the milking sampler every 20 s.

2.3. Reference Analysis

A MilkoScan instrument was used to measure the three major milk quality indicators (milk fat, protein, lactose), and SNF, while a Fossomatic instrument was used to measure SCC. Both instruments are from Foss Electric, Hillerod, Denmark. A total of 377 milk samples were used for the reference analyses.

2.4. Chemometric Analysis

Statistical analyses were conducted to create calibration models for each milk quality indicator and to confirm the models' precision and accuracy. The analyses were conducted using the Unscrambler ver. 10.3 from Camo AS Trondheim, Norway, which analyzes spectral data. The total data from the reference analyses were randomly divided into two datasets, so that two-thirds of all data were used as a calibration set and the remaining data (one-third) were used as a validation set. The calibration models were created from the absorbance spectral and reference data using the partial least squares regression (PLSR) technique. A pretreatment method such as Gap-Segment derivative was used because the best models were produced when we used the pretreated spectra data.

3. Results and Discussion

3.1. Near-Infrared Spectra

Figure 3 shows the original raw milk spectra. The NIR spectra revealed two bands, with peaks at approximately 740 nm and 840 nm, respectively. These bands represent the overtone absorptions by C-H bands and C-C bands, which are connected to the unique absorption bands of milk components, like fat, protein, lactose, and SNF. O-H functional groups in water had a high absorption peak, which made the band at around 960 nm stand out in the spectra.

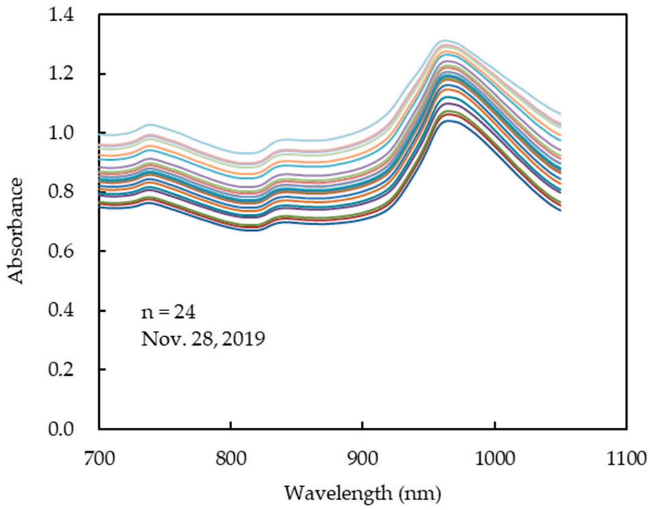

Figure 3. Original spectra of raw milk from cow number 1 during milking on 28 November 2019.

3.2. Calibration Model's Precision and Accuracy (Measurement Results at Every 20 s)

Table 2 summarizes the validation results of the NIR spectrometer for the quality measurement of milk quality indicators. The correlations between reference and NIR predicted values of the milk fat content and SCC are shown in Figures 4 and 5, respectively.

Table 2. Validation statistics of near-infrared spectrometer for milk quality measurement at every 20 s during milking.

Milk Quality Indicators	n1	n2	Range	r^2	SEP	Bias	RPD	Regression Line
Fat (%)	252	125	0.98–8.54	0.99	0.17	0.01	8.86	y = 1.03 x − 0.11
Protein (%)	252	125	2.76–4.46	0.79	0.22	0.01	2.16	y = 0.91 x + 0.31
Lactose (%)	252	125	3.99–4.97	0.71	0.12	0.01	1.86	y = 0.98 x + 0.07
SNF (%)	252	125	8.15–10.09	0.71	0.25	0.03	1.83	y = 0.92 x + 0.71
SCC (log SCCmL^{-1})	252	125	3.70–6.47	0.65	0.44	-0.02	1.69	y = 1.02 x − 0.09

n1: number of calibration samples. n2: number of validation samples. r^2: coefficient of determination value of validation set. SEP: standard error of prediction. RPD: Ratio of SEP to standard deviation of reference data. Regression line: Regression line from predicted value (x) to reference value (y). SNF: Solids not fat. SCC: Somatic cell count.

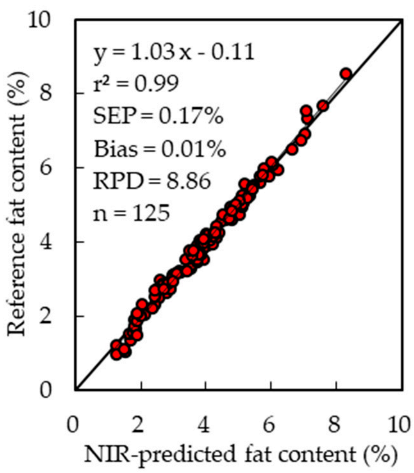

Figure 4. Correlation between reference fat content and NIR-predicted fat content at every 20 s during milking.

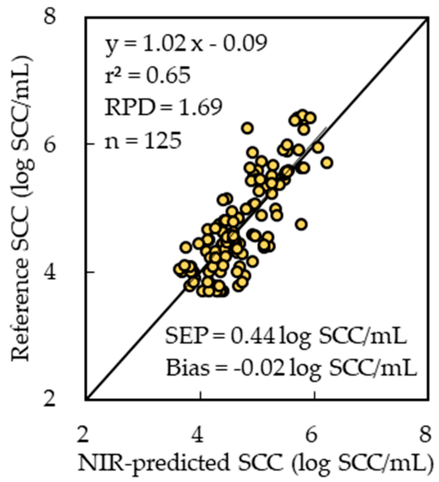

Figure 5. Correlation between reference SCC and NIR-predicted SCC at every 20 s during milking.

For predicting milk fat, protein, lactose, SNF and SCC, the coefficient of determination (r^2), standard error prediction (SEP), and bias were 0.99, 0.17% and 0.01% for milk fat content, 0.79, 0.22% and 0.01% for milk protein content, 0.71, 0.12% and 0.01% for milk lactose, 0.71, 0.25% and 0.03% for SNF, and 0.65, 0.44 log SCC/mL and −0.02 log SCC/mL, respectively. The high r^2 values, low SEP values, and negligible bias values (almost zero) were indicative of high precision and accuracy. The calibration model for milk fat performed very well. The exceptionally high accuracy was made possible by the fact that triacylglycerol's carbon-hydrogen strings were well-represented in NIR spectra. These findings suggested that the NIR could be used to measure the three major milk quality indicators of raw milk, and SNF of each cow during milking. The level of precision and accuracy for predicting SCC was adequate. SCC is a globally recognized indicator of cow subclinical mastitis disease, and the calibration model created for SCC could be used to diagnose subclinical mastitis. As a result, the online NIR spectrometer integrated into an automatic milking system could be used to continuously monitor the physiological state of each cow during milking in real-time.

3.3. Milk Analysis at One Milking Time

Table 3 presents the validation results of the NIR spectrometer for milk quality measurement at a single milking of all cows. The correlations between reference and NIR predicted values of the milk fat content and SCC are shown in Figures 6 and 7, respectively.

Table 3. Validation statistics of near-infrared spectrometer for milk quality measurement at one milking time.

Milk Quality Indicator	n	Range	r^2	SEP	Bias	RPD	Regression Line
Fat (%)	20	1.96–5.79	0.98	0.15	0.05	6.92	y = 0.98 x + 0.01
Protein (%)	20	2.89–4.17	0.83	0.18	−0.07	2.43	y = 0.96 x + 0.22
Lactose (%)	20	4.22–4.85	0.87	0.08	0.01	2.50	y = 1.22 x − 1.01
SNF (%)	20	8.59–9.82	0.94	0.10	−0.02	4.08	y = 0.96 x + 0.37
SCC (log SCC/mL)	20	4.00–6.47	0.83	0.36	−0.17	2.12	y = 1.35 x − 1.49

n: number of milking times. r^2: coefficient of determination value of validation set. SEP: standard error of prediction. RPD: Ratio of SEP to standard deviation of reference data. Regression line: Regression line from predicted value (x) to reference value (y). SNF: Solids not fat. SCC: Somatic cell count.

For each milk quality indicator measured, the validation results, r^2, SEP, and bias values were high, low, and negligible, respectively. The r^2, SEP, and bias values obtained for milk fat, protein, lactose, SNF and SCC, were 0.98, 0.15% and 0.05% for milk fat content, 0.83, 0.18% and −0.07% for milk protein content, 0.87, 0.08% and 0.01% for milk lactose, 0.94, 0.10% and −0.02% for SNF, and 0.83, 0.36 log SCC/mL and −0.17 log SCC/mL, respectively. According to the validation results, the accuracy of these calibration models for measuring each milk quality indicator at one milking time was very high.

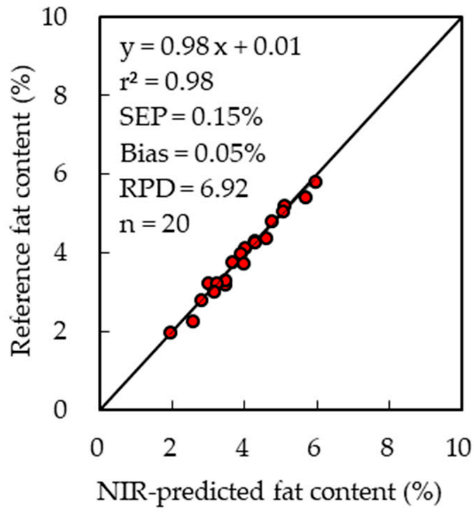

Figure 6. Correlation between reference fat content and NIR-predicted fat content at one milking time.

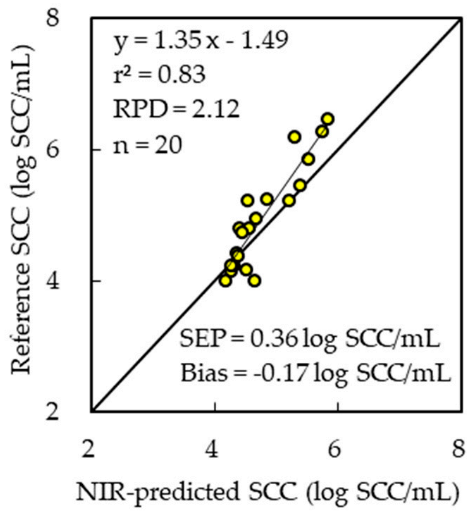

Figure 7. Correlation between reference SCC and NIR-predicted SCC at one milking time.

SEP values were used as a significant statistical indicator for the effectiveness of the calibration models created in this study. As a result, each milk quality indicators' precision and accuracy at intervals of 20 s during milking and at one milking time were nearly the same. This means that it may be possible to measure each cow's milk quality and physiological state by keeping records of milk quality predicted values at each milking time using the NIR spectrometer developed in this study.

3.4. Dairy Precision Farming

The integration of the NIR spectrometer we developed into an automatic milking system would make it easier to measure milk quality indicators and diagnose mastitis in each cow in real-time while they are being milked. The NIR spectrometer may offer dairy farmers and veterinarians' helpful information on the physiological state of each cow and the quality of their milk, providing assessment control for better dairy farm management. By using this NIR spectrometer, dairy farm management could advance to the next stage of dairy precision farming using data from each cow.

4. Conclusions

During milking via an automatic milking system, the online NIR spectrometer developed in this research can be used to monitor milk fat, protein, lactose, SNF, and SCC in real-time. By way of application, dairy farmers would be able to produce milk of the highest quality, and dairy precision farming would become a reality.

Author Contributions: Conceptualization, S.K. and P.I.; methodology, S.K., P.I, T.M. and T.K.; software, S.K. and P.I.; validation, P.I. and S.K.; formal analysis, P.I., S.K. and T.M.; investigation, P.I., S.K., T.M. and T.K.; data curation, P.I. and S.K.; writing-original draft preparation, P.I., writing-review and editing, S.K., T.M. and P.I. All authors have read and agreed to the published version of the manuscript.

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