engineering proceedings

Proceeding Paper

Cow Milk Quality Determination Using a Near-Infrared Spectroscopic Sensing System for Smart Dairy Farming †

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† Presented at the 10th International Electronic Conference on Sensors and Applications (ECSA-10), 15–30 November 2023; Available online: https://ecsa-10.sciforum.net/.

Abstract: This study investigated the accuracy of a near-infrared spectroscopic sensing system for predicting milk quality indicators in cow milk. The system determined three major milk quality indicators (milk fat, protein, and lactose), milk urea nitrogen (MUN), and somatic cell count (SCC) of two Holstein cows at the Hokkaido University dairy farm. The results showed excellent accuracy for milk fat and protein contents, while sufficient accuracy was found for lactose, MUN, and SCC. This suggests that the NIR spectroscopic sensing system could be used for online real-time milk quality determination, aiding dairy farmers in effective individual cow management and smart dairy farming.

Keywords: near-infrared spectroscopy; sensing system; calibration models; milk quality; milk urea nitrogen; somatic cell count; smart dairy farming

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Citation: Iweka, P.; Kawamura, S.; Mitani, T.; Kawaguchi, T. Cow Milk Quality Determination Using a Near-Infrared Spectroscopic Sensing System for Smart Dairy Farming. *Eng. Proc.* **2023**, *58*, 118. https://doi.org/10.3390/ecsa-10-16020

Academic Editor: Stefano Mariani

Published: 15 November 2023

1. Introduction

Smart dairy farming technologies are used to continually and in real time determine cattle milk and health quality indicators in order to maximize nutrition and productivity and to discover health problems at an early stage [1–4]. The ability to determine the three major milk quality indicators, such as milk fat, protein, and lactose; milk urea nitrogen (MUN), which is the nutritional indicator; and somatic cell count (SCC), which is the mastitis disease indicator, from milk samples taken during milking using near-infrared spectroscopy (NIRS) has grown in popularity [5–7].

NIRS is an appropriate technology for assessing milk quality during the milking process due to its non-invasive, quick, user-friendly, time-saving, and pretreatment-free characteristics [8]. NIRS has been utilized to determine agricultural items such as rice, wheat, pomegranate, and other vegetables and to offer qualitative and quantitative information [9–12]. In Japan, NIRS has been used to determine rice quality [9].

Numerous studies have been carried out on the development of online near-infrared (NIR) sensing systems that could help dairy farmers navigate the challenges that come with individual cow management, but there has been difficulty in developing an efficient and sustainable NIR sensing system [13–16]. According to Iweka et al. [17,18], the developed NIR spectroscopic sensing system might be utilized to accurately and precisely measure the quality of the milk of individual cows while milking in real-time. Nevertheless, the actual application of the NIR sensing system for real-time online identification of each cow's milk quality while milking has yet to be realized. One of the major reasons is the measurement accuracy of the sensing system [19].

Therefore, we developed an experimental online NIR spectroscopic sensing system for milk quality determination of individual cows during milking. The goal of this study was to assess both the precision and accuracy of the developed novel NIR spectroscopic sensing system in our study for individual cow milk quality determination every 20 s during milking.

2. Materials and Methods

2.1. Description of the Near-Infrared Spectroscopic Sensing System

To determine the quality of each cow's milk during milking, an experimentally based online NIR spectroscopic sensing system was created. The system included an NIR spectrum sensor, an NIR spectrometer, a milk flowmeter, a sampler, and a laptop computer (Figure 1). The system was linked between a teatcup cluster and the milking system's milking bucket. Through a bypass, raw milk from the teatcup cluster was constantly flowing into the milk chamber (sample cell) of the NIR spectrum sensor. The extra milk flowed down a line tube past the milk flowmeter and into the bucket (Figure 1). The volume of the milk in the NIR milk chamber is about 30 mL (Table 1). The optical axes of halogen lamps A and B were positioned at the same height as the optical fiber, whereas the optical axes of halogen lamp C were set 5 mm higher (Figures 2–4). The milk chamber of the NIR spectrum sensor has a path length of 100 mm and a diameter of 16 mm (Figure 2). The NIR spectrum sensor collected absorbance spectra via the milk. During milking, the spectra were taken at 1 nm intervals every 20 s in the 700 nm to 1050 nm range. The milk flow rate was also recorded on the laptop computer.

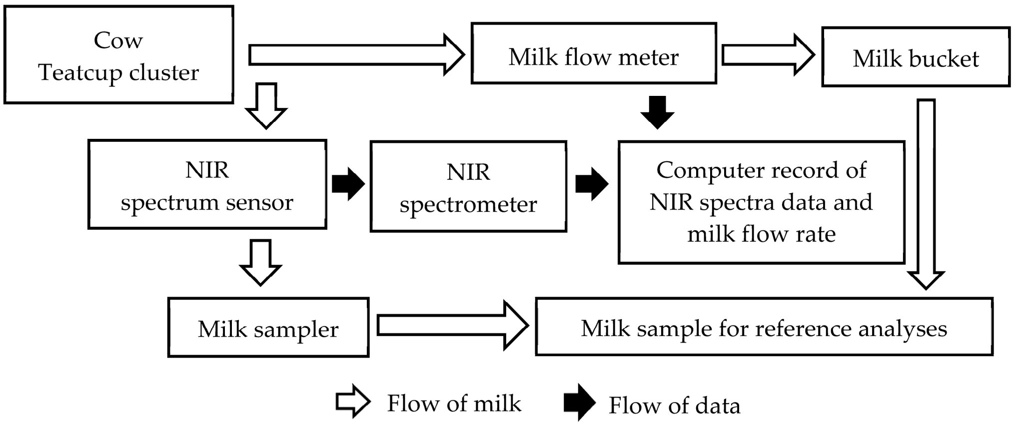

Figure 1. Flow chart of an on-line real-time near-infrared spectroscopic sensing system for determining milk quality indicators during milking. Adapted from [18] with permission from Environmental Control in Biology, 2020.

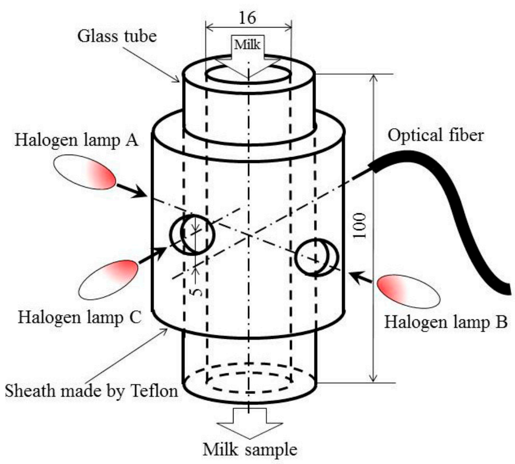

Figure 2. Schematic of the optical system of the NIR spectrum sensor's milk chamber. Adapted from [20] with permission from MDPI, 2023.

Table 1. Specifications of the near-infrared (NIR) spectroscopic 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

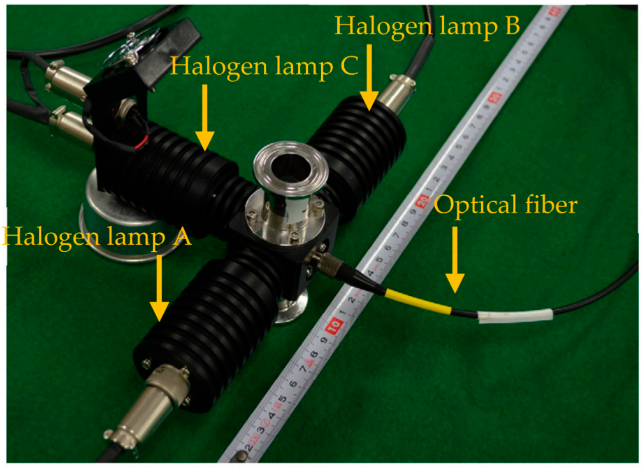

Figure 3. Original NIR spectrum sensor.

2.2. Holstein Cows and Milk Samples

In this study, we used two Holstein cows belonging to the Hokkaido University dairy barn in Japan. The lactation phases of these cows varied. During the experiment, the measurements were taken during two consecutive milkings, one in the evening and one in the morning. On the Hokkaido University dairy farm, cows were milked using a pipeline milking system. Milk spectra and flow data were collected, and raw milk samples were drawn from the milk sampler every 20 s during milking.

2.3. Reference Analysis

The MilkoScan device was used to determine the three primary milk quality indices and MUN, while the Fossomatic device was utilized for estimating SCC. The two devices are from Foss Electric, Hillerod, Denmark. The reference analyses involved 142 milk samples.

2.4. Chemometric Analysis

Statistical investigations were conducted to generate calibration models for each milk quality indicator and to validate the model's accuracy as well as precision. The analyses were carried out utilizing the spectra data analysis technique, the Unscrambler ver. 10.3 from Camo AS Trondheim, Norway. The total data from the reference analyses were used to develop calibration using the full cross-validation method. The calibration models were built using the partial least squares regression (PLSR) method from the absorbance spectra and reference data. No data pretreatment method was used for this analysis.

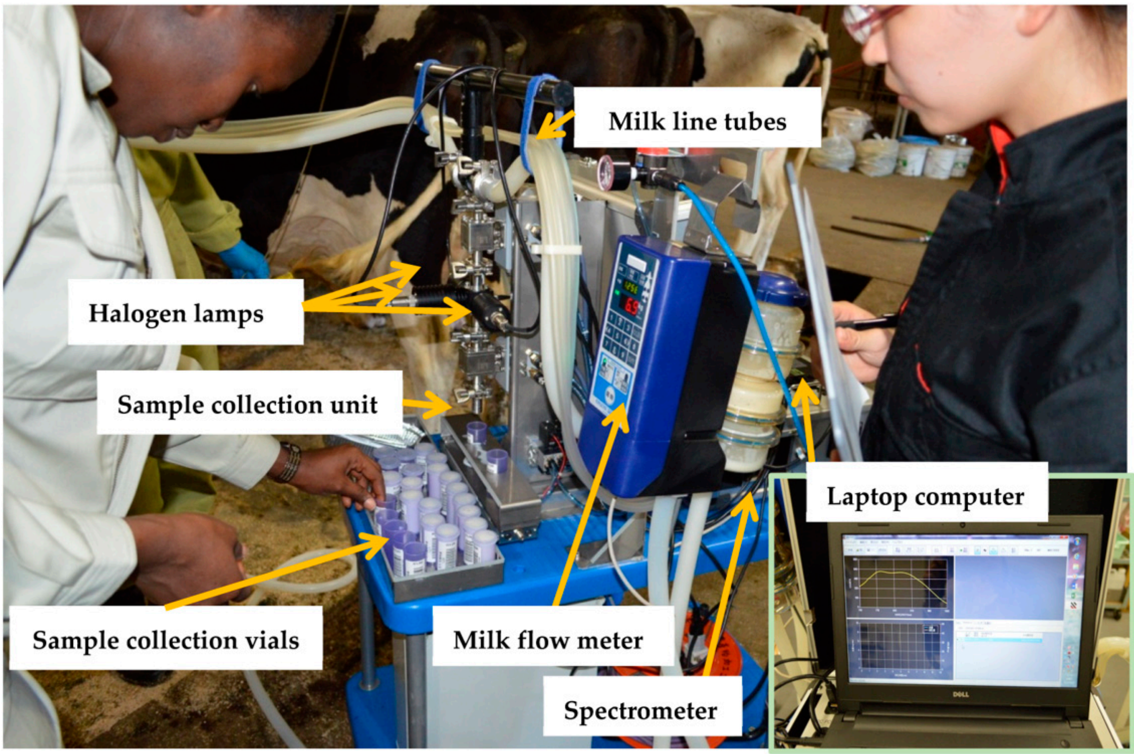

Figure 4. Overview of the NIR spectroscopic sensing system.

3. Results and Discussion

3.1. Near-Infrared Spectra

Figure 5 shows the original raw milk spectra. The NIR spectra indicated a pair of bands, having peaks at 740 and 840 nm, respectively. These peaks represent overtone absorptions by the C-H and C-C bands, which are associated with the different absorption bands of milk components such as fat, protein, and lactose. The O-H functional groups found in water exhibited an elevated absorption peak, distinguishing the spectra band at about 960 nm [15].

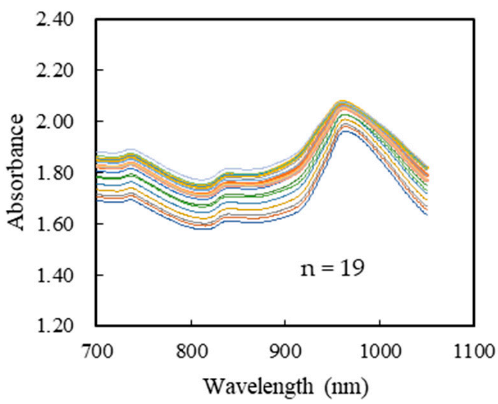

Figure 5. The original spectra of raw milk from cow number 1256 during milking.

3.2. Calibration Models' Precision and Accuracy

Table 2 summarizes the validation results of the NIR spectroscopic sensing system utilized to determine milk quality indicators. The relationships between the reference and NIR-predicted values of the milk fat content and SCC are shown in Figures 6 and 7, respectively.

Table 2. Validation statistics of the near-infrared sensing system for milk quality determination.

Milk Quality Indicators	n	Range	R^2	SEP	Bias	RPD	Regression Line
Fat (%)	142	2.1–6.8	0.98	0.12	0.00	8.05	y = 1.00x + 0.01
Protein (%)	142	3.3–3.8	0.92	0.03	0.00	3.58	y = 0.99x + 0.04
Lactose (%)	142	3.9–4.7	0.70	0.09	0.00	1.83	y = 0.96x + 0.18
MUN (mg/dL)	142	8.9–13.8	0.45	0.60	0.00	1.35	y = 0.92x + 0.97
SCC (log SCCmL^{-1})	142	5.2–6.8	0.60	0.22	0.00	1.58	y = 0.94x + 0.36

n: 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). MUN: milk urea nitrogen. SCC: Somatic cell count.

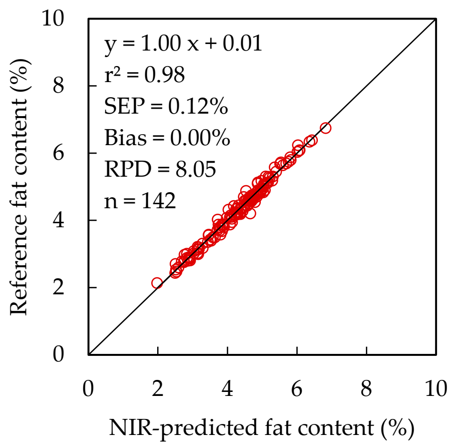

Figure 6. Correlation between reference fat content and NIRS-predicted fat content.

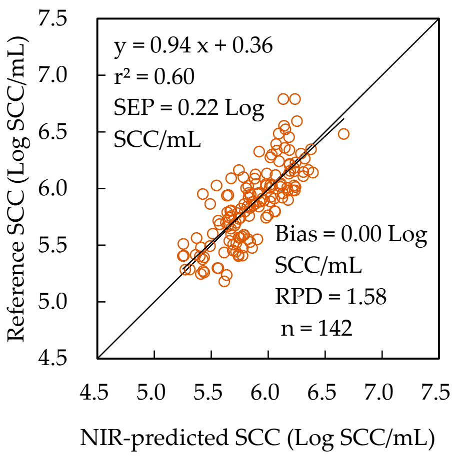

Figure 7. Correlation between reference SCC and NIRS-predicted SCC.

For predicting milk fat, protein, lactose, MUN, and SCC, the coefficient of determination (r^2), standard error prediction (SEP), and bias were 0.98, 0.12%, and 0.00% for milk fat content; 0.92, 0.03%, and 0.00% for milk protein content; 0.70, 0.03%, and 0.00% for milk lactose; 0.45, 0.60%, and 0.00 mg/dL for MUN; and 0.60, 0.22 log SCC/mL, and 0.00 log SCC/mL, respectively. The high r^2 values and low SEP and bias values were indicative of high levels of precision and accuracy. The calibration model for milk fat worked quite well. The carbon–hydrogen strings of triacylglycerol were adequately represented in the NIR spectra, allowing for extraordinarily high precision. These findings suggested that the NIR could be used to determine the three major milk quality indicators of raw milk and the MUN and SCC 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.

3.3. Near-Infrared Sensing System

The accuracy for determining the three major milk quality indicators, MUN, and SCC was very good, especially for milk fat and protein, as compared to the accuracy of the previous NIR sensing system [6]. The cylindrical structure of the NIR spectrum sensor contributed to its high accuracy by reducing the effect of air bubbles and fluctuations in milk flow. Another explanation is that the NIR spectroscopic sensing system used in our work has three halogen lamps that were used as near-infrared light sources to irradiate the milk samples from three directions with an exposure length of 200 ms, which was repeated ten times in one experimental run. It was discovered that our NIR sensor, which is comprised of three halogen lamps, accurately collected the near-infrared light by fat content, as opposed to the prior study's single halogen lamp [6]. As a result, a strong signal was produced. The exposure time ensured that the important bright part of the captured spectra was not lost, resulting in a reduction in various random and fixed pattern noises.

This indicates that the NIR sensing system might provide dairy farmers and vets with useful information on each cow's physiological state and milk quality, providing evaluation control for better dairy farm management. By deploying the data from each cow, dairy farm management might proceed to the next step of smart dairy farming by using this NIR sensing technology.

4. Conclusions

The NIR spectroscopic sensing system created in this study might be utilized to determine the three major milk quality indices, MUN and SCC, of each cow during milking in real time. Further research should be undertaken to improve the precision and accuracy of the proposed calibration models, allowing for the practical implementation of this NIR sensing technology, resulting in smart dairy farming.

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.

Funding: This study was funded by a grant from the National Agriculture and Food Research Organization (NARO) of Japan named Project for Development of New Practical Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The content of this paper summarizes all the new data obtained in this study.

Conflicts of Interest: The author Takashi Kawaguchi works for Orion Company in Nagano, Japan. He worked in collaboration with the authors from Hokkaido University, Japan. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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