TITLE
Near-Infrared Spectroscopic Sensing System for Online Monitoring of Milk Quality during Milking

SHORT RUNNING HEAD
NIR Spectroscopy for Milk Quality

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ABSTRACT

There has been a need in recent years for a method that will enable dairy farmers to monitor milk quality of individual cow during milking. We constructed a near-infrared (NIR) spectroscopic sensing system for online monitoring of milk quality on an experimental basis. This system enables NIR spectra of unhomogenized milk to be obtained during milking over a wavelength range of 600 nm to 1050 nm. We developed calibration models for predicting three major milk constituents (fat, protein and lactose), somatic cell count (SCC) and milk urea nitrogen (MUN) of unhomogenized milk, and we validated the precision and accuracy of the models. The coefficient of determination (r^2) and standard error of prediction (SEP) of the validation set were obtained: for fat, $r^2 = 0.95$, SEP = 0.42%; for protein, $r^2 = 0.91$, SEP = 0.09%; for lactose, $r^2 = 0.94$, SEP = 0.05%; for SCC, $r^2 = 0.82$, SEP = 0.27 log SCC/mL; and for MUN, $r^2 = 0.90$, SEP = 1.33 mg/dL, respectively. These results indicated that the NIR spectroscopic sensing system developed in this study could be used to monitor milk quality in real-time during milking. The system can provide dairy farmers with information on milk quality and physiological condition of each cow and therefore give them feedback control for producing milk of high quality and for optimizing dairy farm management.

KEYWORDS
Near-infrared spectroscopy, NIR, dairy farming, milk quality, quality control, diagnosis

INTRODUCTION

Dairy farming is labor-intensive and involves many tasks such as feeding, milking, livestock management, feed crop production and manure treatment. Large-scale dairy farmers manage their livestock in groups, a system known as herd management. The three major milk constituents (fat, protein and lactose), somatic cell count (SCC) and milk urea nitrogen (MUN) are very important indices of milk quality. To know the milk quality of each cow, dairy farmers in Hokkaido, the northernmost island of Japan, take milk samples during milking and send them to Hokkaido Dairy Milk Recording & Testing Association for examination once a month. However, monitoring milk quality of each cow and managing each cow, a system known as individual cow management, is essential for producing high-quality milk. Therefore, there has recently been a strong need for a method that will enable dairy farmers to monitor milk quality of each cow during milking every day.

Near-infrared spectroscopy (NIRS) is a new nondestructive sensing method for obtaining qualitative information on foods and agricultural commodities. NIRS has already been used for determining physicochemical properties of rice[1] and has been put to practical use in automatic rice-quality inspection systems in Japan[2]. NIRS has also been used to assess milk quality[3-7], but the milk quality was measured by using an NIR instrument set in a laboratory room. It has been difficult to apply NIRS for real-time online monitoring of milk quality during milking.

We have constructed a near-infrared (NIR) spectroscopic sensing system on an experimental basis for online monitoring of milk quality during milking, and we validated the precision and accuracy of the calibration models developed by the sensing system for monitoring milk quality in this study.

MATERIALS AND METHODS

Near-infrared spectroscopic sensing system

An NIR spectroscopic sensing system for online monitoring of milk quality of each cow during milking was constructed on an experimental basis. The system consisted of an NIR instrument, a milk flow meter and a milk sampler (Figures 1 and 2).

The system was installed between a teatcup cluster and a milk bucket of a milking machine. During milking unhomogenized milk from the teatcup cluster continuously flowed into the milk chamber monitored by the NIR spectrum sensor and flowed out through an outlet pipe for surplus milk to the milk flow meter by the negative pressure of the milking machine (Figures 2 and 3). The milk that flowed out from the milk flow meter continuously flowed into the milk sampler and then into a milk bucket. The optical axes of a halogen lamp and optical fiber were set to the same level (Figure 3). The volume of milk sample in the chamber was about 230 mL. The spectrum sensor acquired diffusion transmittance spectra through the milk. The spectra were recorded in the range of 600 to 1050 nm at 1-nm intervals (451 data points) every 10 seconds during milking (Table 1). Six continual spectra were averaged to obtain a spectrum for one minute.

Cows and milk samples

Four Holstein cows in the stage of early lactation to late lactation were used in the experiment (Table 2). The experiment was started on October 23, 2001 and continued until June 12, 2002. Measurements were carried out in two consecutive milkings, i.e., milking in the evening and milking in the next morning, every two weeks during the experimental period. Milk samples were collected from the milk sampler every minute during milking to be used for reference analyses. The experiment was conducted to cover variations in milk spectra caused by cow individuality, calving times, lactation stage, milking time, physiological conditions, feeding

stage and environmental temperature.

Reference analyses

Milk constituents (fat, protein and lactose), somatic cell count (SCC), and milk urea nitrogen (MUN) of unhomogenized milk were measured as indices of milk quality in this study. The milk constituents were determined using a Milkoscan S54A (Foss, Hillerod, Denmark), SCC was determined using a Fossomatic 5000 (Foss), and MUN was determined using a Milkoscan 4000 (Foss). The total numbers of samples used for reference analyses were 455 for milk constituents, 404 for SCC and 236 for MUN. SCC was converted into common logarithm of SCC.

Chemometric analyses

Chemometric analyses were carried out to develop calibration models for milk quality items and to validate the precision and accuracy of the models. Spectral data analyses software (The Unscrambler, Camo AS, Trondheim, Norway) was used for the analyses. The reference data were randomly divided into two data sets: a calibration subset containing two-thirds of all data and a validation subset containing the remaining data (one-third). The statistical method of partial least squares (PLS) regression was used to develop calibration models from the transmittance spectra and reference data. Pretreatment of the spectra such as smoothing or derivatives was not performed.

RESULTS AND DISCUSSION

Near-infrared spectra

Figure 4 shows an example of an original NIR spectra set of unhomogenized milk from cow number 1116 in morning milking on January 9, 2002. The deep valley of the spectra in the wavelength range of 960 to 990 nm in Figure 4 indicates the second overtone absorption by water molecules. The two valleys in the spectra around 740 nm and 840 nm indicate the overtone absorptions by C-H strings and C-C strings that are associated with milk fat (triacylglycerol).

Number of PLS factors

Multivariate calibration in PLS consists of estimating model parameters, including number of factors to use in the model. Using too few factors can leave important NIR spectra unmodeled, and using too many factors draws too much measurement noise form NIR spectra into the calibration model[8]. The optimal number of PLS factors for determination of milk quality was determined as the number of factors after which explained variance no longer increased significantly. Explained variances versus number of PLS factors are shown in Figure 5. Explained variance (EV) and number of PLS factors (NPF) for determination of milk quality were obtained: for fat, EV = 95%, NPF = 7; for protein, EV = 91%, NPF = 13; for lactose, EV = 94%, NPF = 12; for SCC, EV = 82%, NPF = 12; and for MUN, EV = 91%, NPF = 13. The explained variances obtained by using the NIR spectroscopic sensing system were high enough for determination of each milk quality item.

Loading weight for PLS factors

Loading weight for the first three PLS factors to predict fat content is shown in Figure 6. The first factor had the highest contribution of 61% to explain variance of fat, the second factor had 17% and the third factor had 11% (Figure 5). High negative loading weights of PLS factor 1 were found in the wavelength range between 600 to 900 nm, and very low loading weights were found around 960 to 990 nm. The area around 960 to 990 nm is dominated by water absorption.

This result indicates that PLS factor 1 explained fat variance excluding water influence. On the other hand PLS factors 2 and 3 explained fat variance including water influence because of the positive loading weight of PLS factors 2 and 3 around 960 to 990 nm.

Precision and accuracy of calibration models

Correlations between reference values and predicted values of fat, protein, lactose, SCC and MUN by the NIR spectroscopic sensing system are shown in Figures 7 to 11, respectively. The validation statistics of each milk quality item are also summarized in the figures.

The coefficient of determination (r^2), standard error of prediction (SEP) and bias of the validation set for fat were 0.95, 0.42% and 0.01%, respectively. The values of r^2, SEP and bias for protein were 0.91, 0.09% and 0.00%, respectively, and the values of r^2, SEP and bias for lactose were 0.94, 0.05% and 0.00%, respectively. Sufficient levels of precision and accuracy for predicting the three major milk constituents were indicated by the high values of r^2 (>0.9), the small values of SEP compared with the range of each constituent, and the negligible values of bias (almost zero). The results indicate that the NIR spectroscopic sensing system constructed in this study is useful for real-time online monitoring of milk constituents during milking.

SCC has been accepted as the world standard for mastitis diagnosis, and it is an important indicator of milk quality. The values of r^2, SEP and bias for SCC prediction were 0.82, 0.27 log SCC/mL and -0.03 log SCC/mL, respectively. Milk containing more than 100,000 somatic cells/mL, i.e., 5.0 log SCC/mL, is of low quality. Using the calibration model for SCC to classify milk samples into two qualitative groups (high quality and low quality) gave a probability for classifying them correctly of 86%[9]. Thus, the model could be used for diagnosis of subclinical mastitis.

MUN is an indicator of protein feeding efficiency in dairy cows. Too little protein in the diet results in poor milk production. On the other hand, too much protein results in infertility of cows and eventually environmental nitrogen contamination through urine and fecal output from cows. The values of r^2, SEP and bias for MUN prediction were 0.90, 1.33 mg/dL and -0.03 mg/dL, respectively. Thus, the calibration model could be used for monitoring the nutritional status of each cow.

Milk-quality monitoring in real time during milking

Figure 12 shows the results of fat content monitoring in cow number 1116 by the NIR spectroscopic sensing system during evening milking on January 8, 2002 and the next morning. Fat content greatly increased from 2.1% to 7.3% during morning milking. There was also a large difference between fat content of evening milk and that of morning milk from the same cow. Raw milk is produced in the mammary alveolus of the udder. The raw milk moves down to the mammary cistern (gland cistern and teat cistern) through the mammary duct and is stored in the mammary cistern until milking. Milk fat stays in the upper part of the mammary alveolus and mammary cistern. Fat content is therefore very low at the beginning of milking and increases during milking. There is residual milk, which is about 15% of total milk quantity in the udder, after milking. The fat content of residual milk is very high. The interval time after morning milking and consecutive evening milking in this experiment was about 9 hours. The milk yield of evening milking was lower than that of morning milking and the fat content of evening milk was higher than that of morning milk because of the influence of high fat content of residual milk.

Protein content of the milk from cow number 1116 was about 3% on average and fluctuated by only 0.4% during evening and the next morning milking. Lactose content gradually decreased from 5.3% to 4.7% during the morning milking. SCC increased from 3.5 log SCC/mL to 4.3 log SCC/mL during the morning milking, and SCC in the evening milking was about 4.7 log

SCC/mL, which was higher than that in the morning milking. MUN linearly decreased from 16 mg/dL to 13 mg/dL during the milking.

Dairy precision farming

Installation of the NIR spectroscopic sensing system developed in this study into a milking robot system would enable monitoring of milk constituents, diagnosis of mastitis and assessment of physiological conditions of cows in real-time during milking. The system could provide dairy farmers with important information on milk quality and physiological condition of each cow and therefore give them feedback control for producing milk of high quality and for optimizing dairy farm management. By using the NIR spectroscopic sensing system, dairy farm management could proceed to the next step in the transition to dairy precision farming based on information of each cow.

CONCLUSION

The NIR spectroscopic sensing system developed in this study can be used for real-time online monitoring of fat, protein, lactose, SCC and MUN during milking with sufficient precision and accuracy. The system can provide dairy farmers with information on milk quality and physiological condition of individual cow and therefore give them feedback control for producing milk of high quality and for optimizing dairy farm management.

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LEGENDS

Figure 1. Flow chart of near-infrared spectroscopic sensing system for online monitoring of milk quality during milking.

Figure 2. Near-infrared spectroscopic sensing system.

Figure 3. Plane view of the near-infrared spectrum sensor constructed on an experimental basis.

Figure 4. Original spectra of unhomogenized milk from cow number 1116 during morning milking on January 9, 2002.

Figure 5. Explained variance for determination of milk quality versus number of PLS factors.

Figure 6. Loading weight for the first three PLS factors to predict fat content.

Figure 7. Correlation between reference fat content and NIRS-predicted fat content.
r^2: coefficient of determination. SEP: standard error of prediction. n: number of validation samples.

Figure 8. Correlation between reference protein content and NIRS-predicted protein content.

Figure 9. Correlation between reference lactose content and NIRS-predicted lactose content.

Figure 10. Correlation between reference SCC and NIRS-predicted SCC.

Figure 11. Correlation between reference MUN and NIRS-predicted MUN.

Figure 12. Fat content monitoring during milking from cow number 1116.

Table 1. Specifications of near-infrared spectroscopic instruments constructed on an experimental basis.

Table 2. Cows used in the experiment.

Table 1. Specifications of near-infrared spectroscopic instruments constructed on an experimental basis.

Devices	Specifications
Spectrum sensor	Diffusion transmittance spectrum sensor
Light source	Halogen lamp
Optical fiber	Silica glass fiber, 0.6-mm diameter
Milk chamber surface	Glass
Volume of milk sample	Approx 230 mL
Distance between optical axis and milk level	93 mm
Spectrometer	Diffraction grating spectrometer
Optical density	Transmittance
Wavelength range	600 - 1050 nm, 1-nm intervals
Wavelength resolution	Approx 5 nm
Photocell	Linear array CCD, 2048 pixels
Thermocontroller	Peltier cooling system
Data processing computer	DELL, Windows XP, Celelon 1.06GHz, RAM 384 MB
A/D converter	12 bit
Spectrum data acquisition	Every 10 seconds

Table 2. Cows used in the experiment.

Cow number	Birthday	Calving date	Calving times	Experimental period Days after calving
1110	Apr. 24, 97	Oct. 25, 2001	3	13 - 210
1116	Apr. 6, 98	Oct. 16, 2001	2	9 - 240
1119	Apr. 21, 98	Nov. 1, 2001	2	34 - 139
1141	Feb. 3, 98	Oct. 26, 2001	2	12 - 230

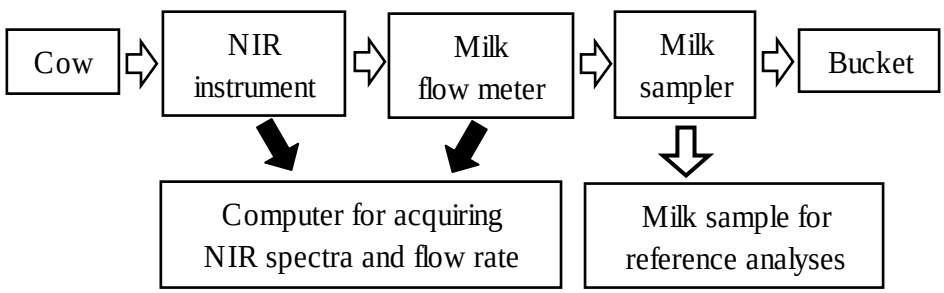


Figure 1. Flow chart of near-infrared spectroscopic sensing system for online monitoring of milk quality during milking.

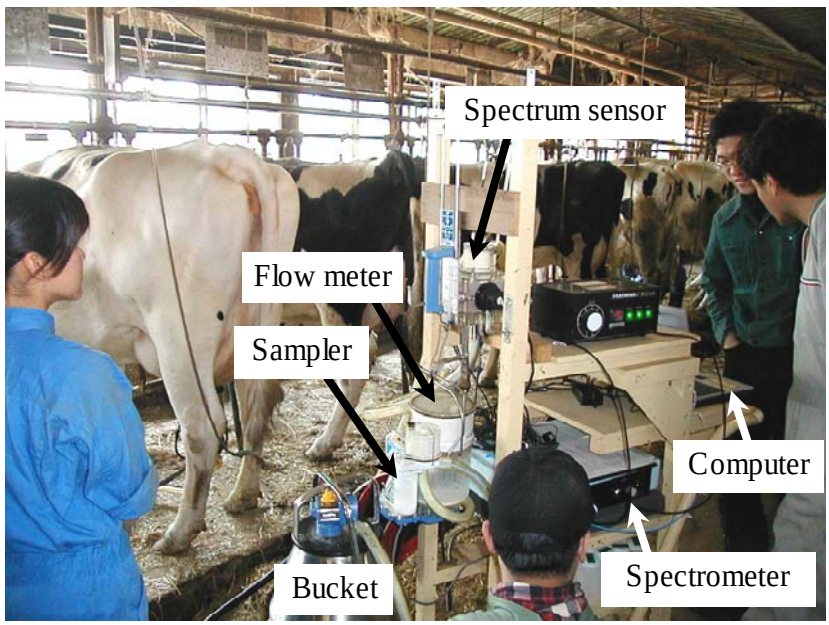


Figure 2. Near-infrared spectroscopic sensing system.

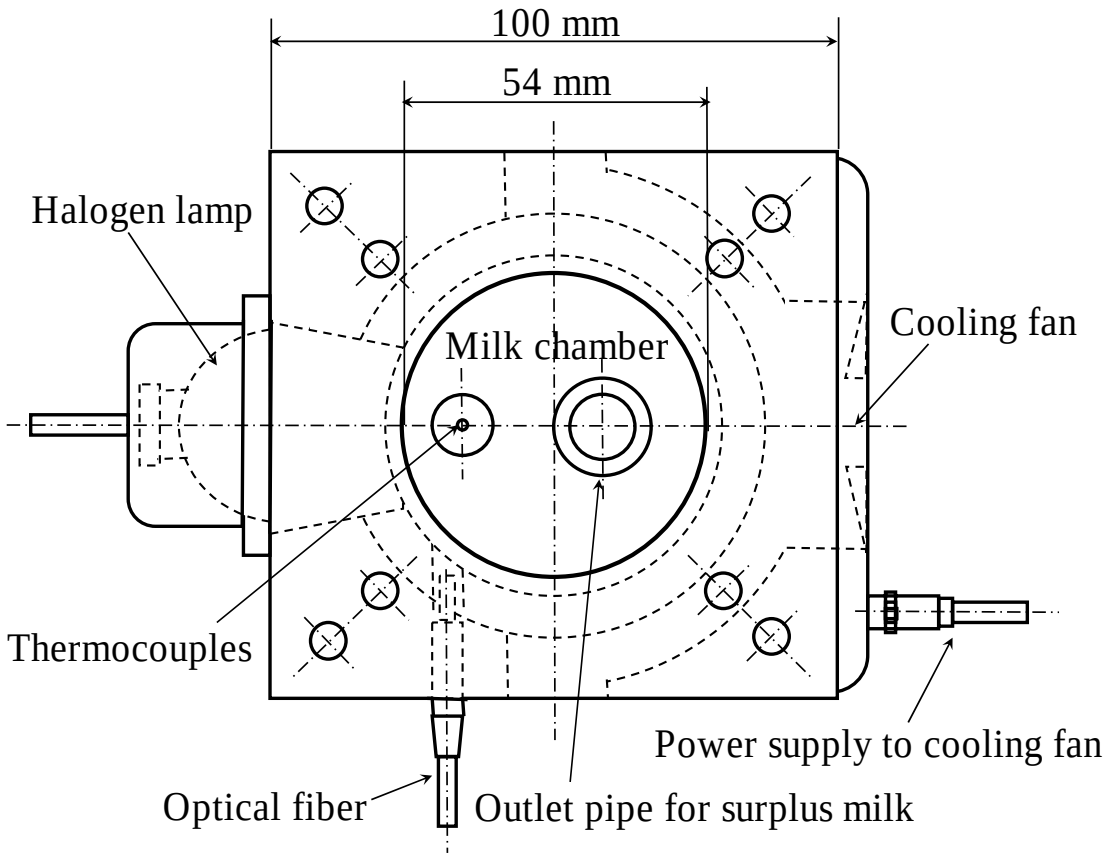
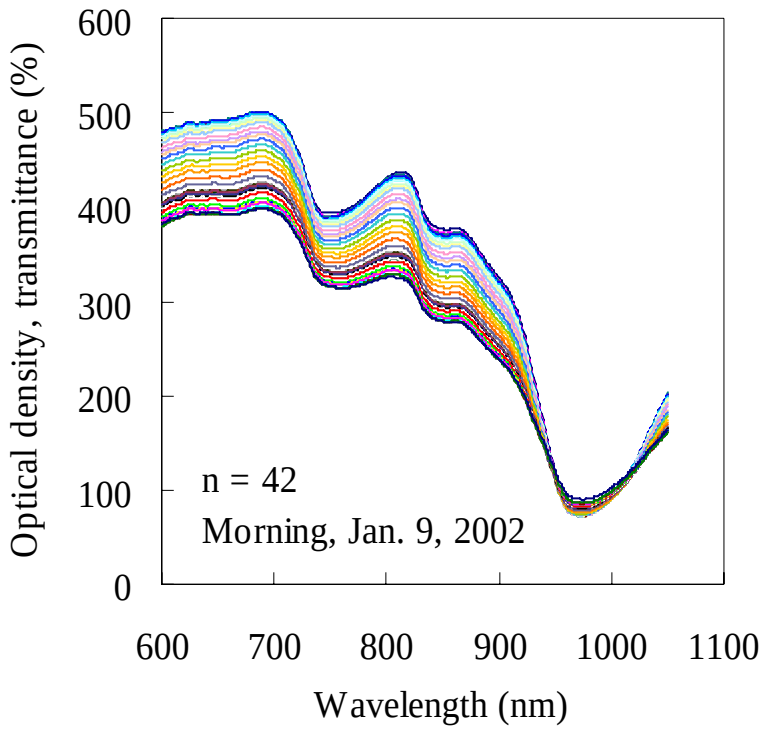


Figure 3. Plane view of the near-infrared spectrum sensor constructed on an experimental basis.



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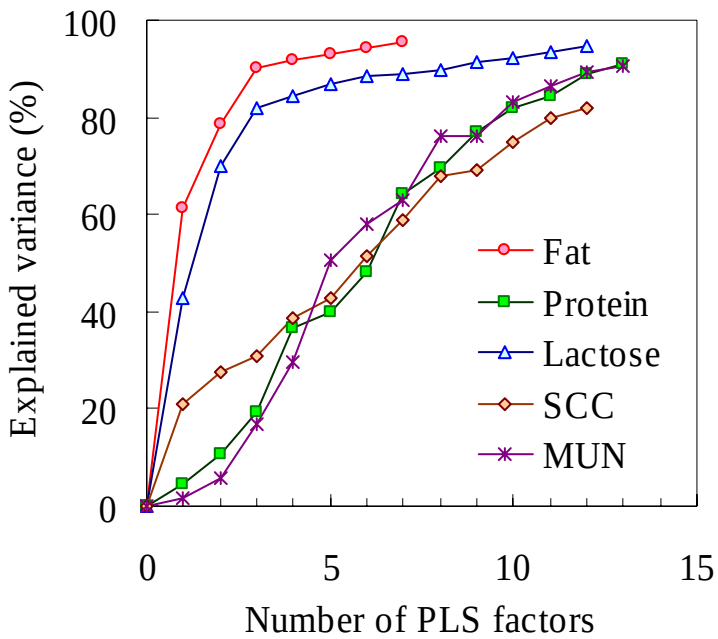

Figure 5. Explained variance for determination of milk quality versus number of PLS factors.

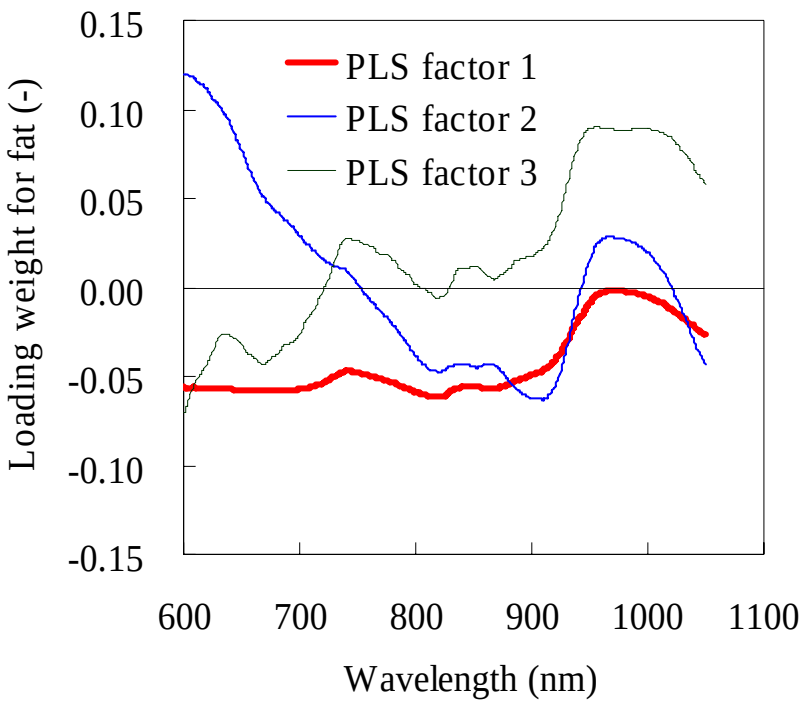

Figure 6. Loading weight for the first three PLS factors to predict fat content.

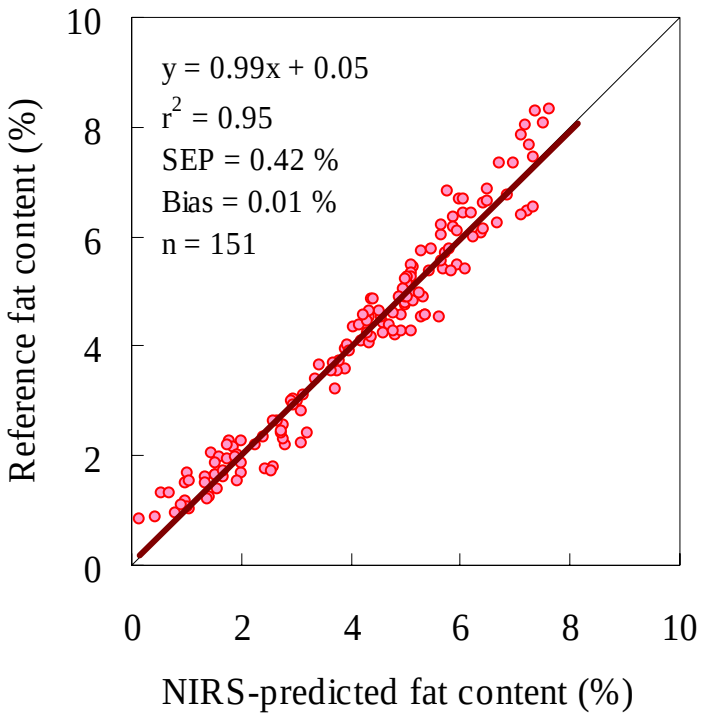

Figure 7. Correlation between reference fat content and NIRS-predicted fat content.
r^2: coefficient of determination. SEP: standard error of prediction. n: number of validation samples.

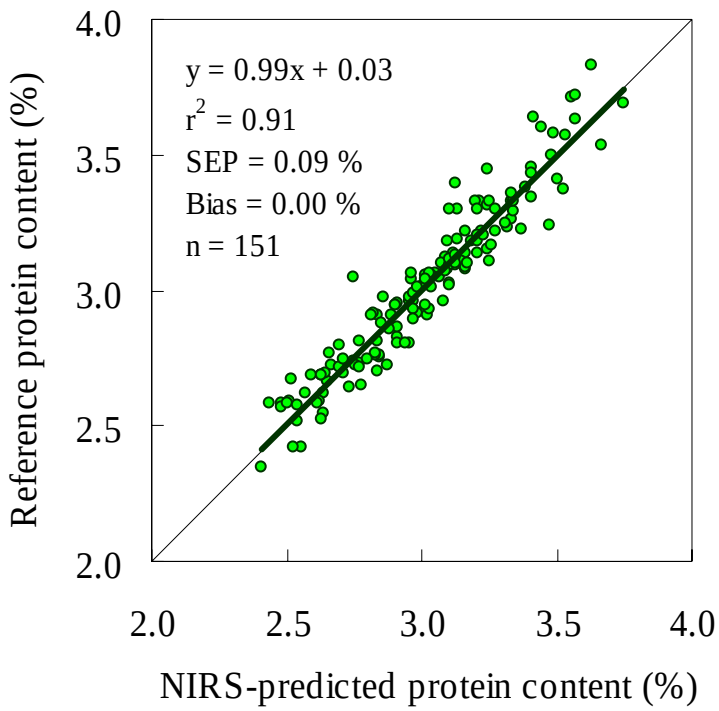

Figure 8. Correlation between reference protein content and NIRS-predicted protein content.

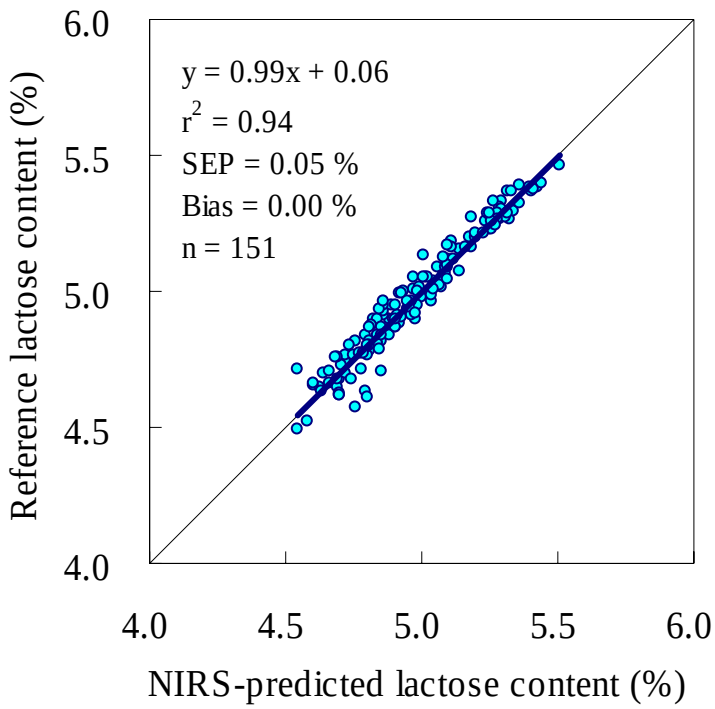

Figure 9. Correlation between reference lactose content and NIRS-predicted lactose content.

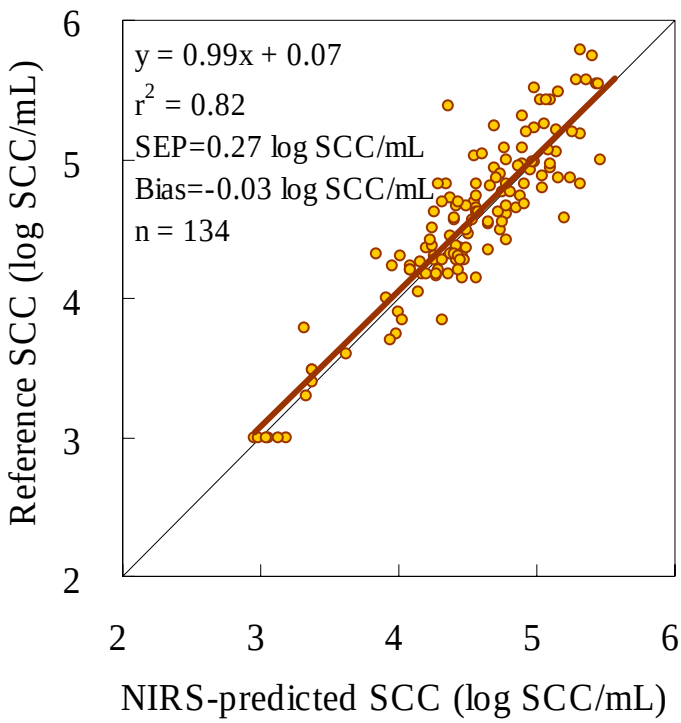

Figure 10. Correlation between reference SCC and NIRS-predicted SCC.

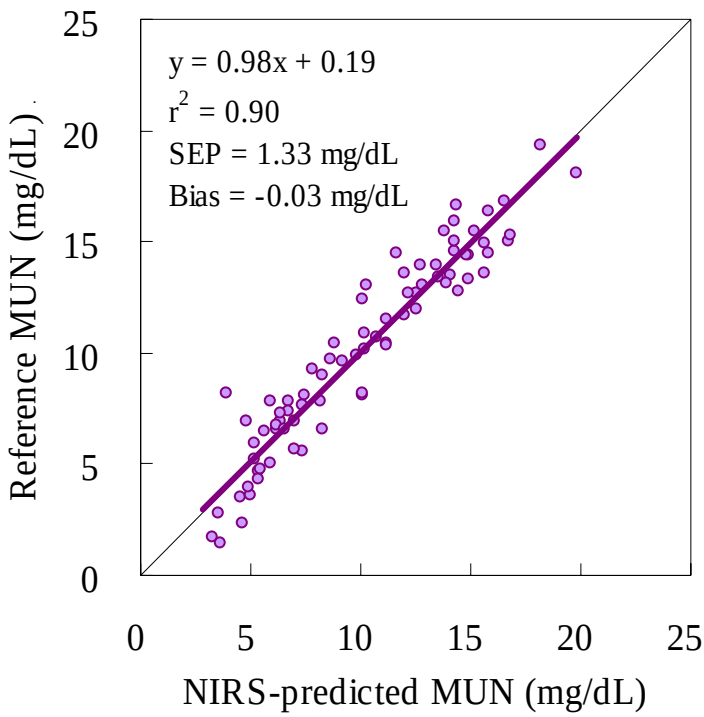

Figure 11. Correlation between reference MUN and NIRS-predicted MUN.

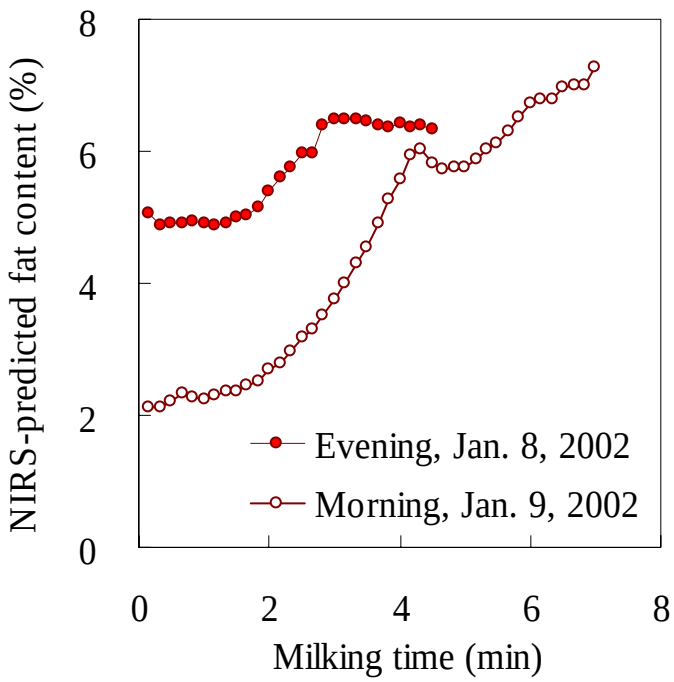

Figure 12. Fat content monitoring during milking from cow number 1116.