**CSIRO** PUBLISHING

*Animal Production Science*, 2021, **61**, 514–524
https://doi.org/10.1071/AN19306

# Optimisation of dry matter and nutrients in feed rations through use of a near-infrared spectroscopy system mounted on a self-propelled feed mixer

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## Abstract

***Context.*** Knowledge of the nutrient requirements of dairy cows, and the nutritional composition and physical form of the feed resources used to prepare the total mixed ration (TMR) of basic and concentrated feeds, is essential to achieving high milk yields, health and welfare in modern commercial herds. Grass and maize silage components can vary widely in composition depending on harvesting intervals and weather; thus, the distribution of dry matter (DM) and nutrients in silos may vary greatly, resulting in serious errors during sampling and analysis. In addition, the flow of information from the stored silage stops once the forages are stored in the silo.

***Aims.*** The objective of this study was to develop a practical approach for measuring variations in DM and silage quality parameters (crude protein, fibre, ash and fat) during the feed-extraction process from a bunker silo by a self-propelled feed mixer, which would ultimately help farmers to optimise the TMR.

***Methods.*** . Near-infrared spectroscopy (NIRS) technology was used to estimate fodder DM and nutrient contents in the material flow. Wet chemical analyses were used for preliminary evaluation of grass and maize silage samples. A portable NIRS was developed to record the spectra of various silage samples.

***Key results.*** The spans of calibration of sample DM content were 21.3–59.2% for grass and 26–46.7% for maize. Crude protein content had span values of 11.4–18.3% for the grass silage and 5.4–10.8% for the maize silage models.

***Conclusions.*** NIRS technology was used successfully to estimate the DM and nutrient contents of the fodder. The location for the functional unit on the self-propelled feed mixer may need to be modified for series production because it is not fully accessible.

***Implications.*** NIRS is a suitable method for measuring DM and nutrient contents continuously during feed extraction from the bunker silo and can be used to help farmers to optimise the TMR.

**Keywords:** dairy cattle, feeding diets, fodder dry matter and nutrient contents, grass and maize silages, near-infrared spectroscopy.

Received 23 May 2019, accepted 19 October 2020, published online 18 November 2020

## Introduction

Milk production in Germany is considered one of the most important outputs of dairy farms. The total quantity of dairy milk produced in Germany in 2016 was 32.7 Mt, produced at 96 200 farms by a national herd of 4.1 million dairy cows (Schoof *et al*. 2020). The increasing demand for dairy milk entails increasing the number of cattle, and thus their feed requirements (Martin *et al*. 2017). Furthermore, the high costs of forage production and concentrates necessitate improved utilisation of the feed components.

A self-propelled feed mixer can save both working time and labour required to feed large dairy herds. The feed mixer has all of the functions that occur in the feeding chain including removal silage from the silo, addition of concentrated feed, mixing all components, and transporting the total mixed ration (TMR) onto the feeding alley with the required feed dosing. The operating parameters of a self-propelled feed-mixer wagon include the number of animals in the barn, the number of stalls, the number of and distances between silos and concentrates containers, and the number of daily diets that need to be mixed.

Animal performance is affected by the content of silage from nutrients (Huhtanen *et al*. 2002). Silage, as an acidic and fermented stored feed produced from different agricultural

crops, is regularly fed to animals on dairy cattle farms (Grant and Adesogan 2018), where it contributes 50–70% of the ration (Petrovska *et al*. 2015). Therefore, identifying the exact composition of the silage at mixing is important for feeding dairy cattle according to their nutritional requirements (Huhtanen *et al*. 2002).

Common crops used to produce the silage are maize (*Zea mays*), grasses, lucerne (*Medicago sativa*), sorghum (*Sorghum bicolor*), legumes, and other alternative cereals (Park *et al*. 2005; Kleinmans *et al*. 2016; Grant and Adesogan 2018). The percentages in basic feed as described by DLG (2013) are 39.7% maize silage, 49.5% grass silage, 5.1% lucerne and 5.7% whole-plant silage such as green rye (*Secale cereale*) silage. Therefore, grass and maize silage are the two main feed components and comprise a large mass fraction in the feed ration. The distribution of dry matter (DM) and nutrient contents at the silo face and even in the whole silo can vary greatly depending on harvesting intervals and weather conditions (Hue *et al*. 2012; Han *et al*. 2014).

Generally, the selection of a ration with specific DM and nutrient contents is based on analyses of laboratory samples. However, laboratory analyses are time-consuming and expensive, require intensive labour, and use hazardous chemicals that could be environmentally detrimental (Kennedy 1996; Stuth *et al*. 2003; Park *et al*. 2005). Further, it is difficult to take a representative sample from the silo for feed analysis. Errors occur not only during sampling as stated by Alomar *et al*. (2009) but also during sample mixing and analysis. Thus, a wide range of DM and nutrient content values in the silage block will lead to significant deviations in the ration composition (Yoder *et al*. 2013).

Near-infrared spectroscopy (NIRS) is being used to examine DM and nutrient contents at harvesting (Yang *et al*. 2017). This technique could be used for large-scale sampling without the intensive labour associated with traditional analytical methods (Stuth *et al*. 2003). However, once the forages are ensiled, monitoring of content is difficult and thus assigning feed batches is problematic. Nonetheless, NIRS provides the possibility for rapid, accurate and non-destructive determination of substrate-specific properties (Stuth *et al*. 2003; Park *et al*. 2005; Stockl *et al*. 2010; Yang *et al*. 2017). NIRS is able to analyse substrates such as grass and maize silages within few seconds and to estimate the values of DM and nutrients directly, by using stored models (Walther *et al*. 2011). The technique could facilitate the assignment of the feed batches to be offered to dairy cows.

The overall aim of the study was to optimise the feeding process of the dairy cows by enhancing the silage quality parameters in the ration. Therefore, DM and other quality parameters such as crude protein (CP), crude fibre (CF) and crude fat (CE) of the stored silage needed to be continuously estimated during feed extraction from the silo. In order to achieve this, NIR measuring technology was installed in a self-propelled fodder-mixing wagon to measure DM and nutrient contents in the material flow. The measured values were then used to modify the mixture in order to create a performance-oriented target ration.

## Materials and methods

### *Determination of silage heterogeneity*

The investigation was done at the Experimental Educational Center for Agriculture 'Haus Riswick', Chamber of Agriculture in Kleve (North Rhine-Westphalia), Germany. The station serves ~560 dairy cattle, using 10 rations for daily feeding. Grass and maize silages were available as feed samples because they exist in almost all TMRs and can show large fluctuations in DM and nutrient contents. Heterogeneity of grass and maize silages in silos was analysed by examining DM and nutrient variations in silos containing 15 pasture-grass silages and 10 maize silages. Two different positions in the silo were sampled because of the daily removal of stored silage as shown in Fig. 1: P1, silo surface at the first day; and P2, middle of silo after 7 extraction days. The samples were collected from nine uniform points on each silage surface (P1 and P2) for grass and maize silages.

A similar sampling method was used for both maize and grass silages from silos. An electrically driven sample drill (56 mm internal diameter and 250 mm long) was built and used to draw out the same sample volumes from the silo. Preliminary evaluation of silage samples obtained from grass and maize silos was done through wet chemical analysis to determine DM, crude ash (CA), CP, CF, CE, starch, sugars, Hohenheim feed test (HFT, *in vitro* gas-production technique), pH, neutral detergent fibre ($NDF_{OM}$), acid detergent fibre ($ADF_{OM}$), usable CP (uCP), and rumen nitrogen balance according to

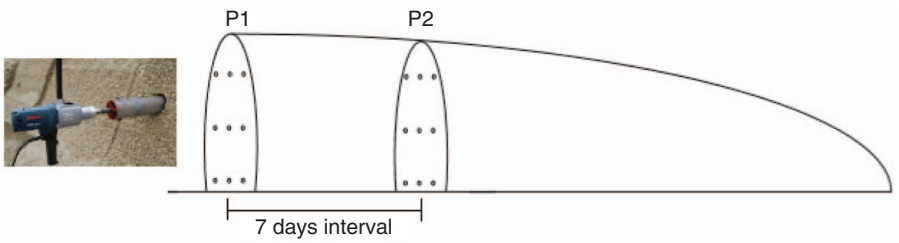



**Fig. 1.** Spatial distribution of sampling from the silo. P1, Sampling at the surface of the silo; P2, sampling at the middle of the silo.

the German standards (Naumann and Bassler 1997). Wet chemical reference analyses for grass and maize silage samples were performed throughout the year and were included in the calibrations. These analyses were conducted in the Certificated Feed Laboratory LKS (Landwirtschaftliche Kommunikations und Servicegesellschaft), Lichtenwalde, Germany.

### *Portable NIRS turntable system*

A portable NIRS turntable system was developed for recording the spectra of various grass and maize silages. With this system, it is possible to measure the feed samples by NIRS directly at the farm. The system comprises the NIRS functional unit and a turntable as shown in Fig. 2. The turntable holds a Petri dish (150 mm diameter, 15 mm depth) at the bottom and centres it in a cylinder. A bearing of 150 mm inside diameter is attached from outside with a pulley. From underneath, a freely accessible Petri dish rotates directly over the sensor head. The rotation of the measured material through the sensor simulates the movement of the material flow (in a similar mode to that occurring in the mixer wagon). The rotation speed of the unit can be varied using an electrical control system. A spectrometer (AvaSpec-NIR256-1.7TEC; Avantes, Apeldoorn, Netherlands) was installed in the portable NIRS turntable system, as well as in the NIRS system mounted on the self-propelled feed mixer.

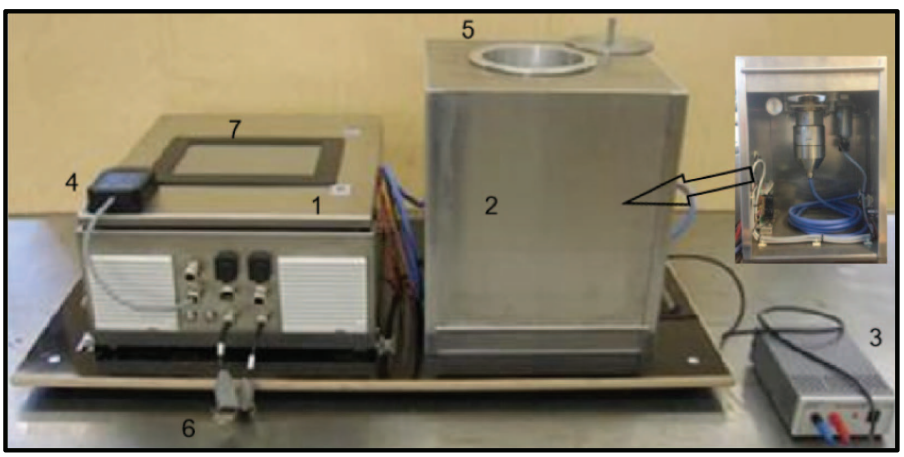
Measurements for the investigated samples of grass and maize silages were performed under a wavelength in the range of 1000–1700 nm, as recommended by Park *et al*. (1998). Silage samples (0.1 kg) were placed in the Petri dish. This weight was selected to improve the compaction in the Petri dish and prevent the re-supply of air into the sample, thereby keeping the chemical composition of the samples constant. The Petri dish was inserted into the turntable under 85 rpm rotational speed. At the beginning of the first measuring day for each silo, a white reference was performed at 60-min intervals. Hence, changes in the radiation intensity of the light source were compensated. During the measurements, reference samples were registered in the database of the measuring system. These stored spectra were compared with the external results determined in the laboratory.

Before taking a reference sample, it was necessary to ensure the active operating status of the sensor head. The time of sampling had to be recorded as accurately as possible so that the corresponding sample was clearly assigned. The input was performed via a barcode scanner, a radio frequency identification reader and an on-screen keyboard. Six measurements were conducted using the portable NIRS turntable system with 10-s intervals. The measurement type was absorption and the exposure time was 10 ms.

After the measurements, the samples were removed from the Petri dish and frozen for wet chemical analyses in the laboratory. During the periods of NIR measurement and laboratory analysis, the individual samples with their DM and nutrient variations were recorded in order to construct a systematic reference database for the calibration of the NIRS measuring system.

### *Installation of the NIRS system on the self-propelled feed-mixer wagon*

The sensor head of the NIRS system was installed on the right part of the milling arm of the self-propelled feed-mixer wagon in the inflow area between the miller and elevator belt. The




1. Functional unit
2. Turntable system
3. Power supply
4. RFID readout unit
5. Petri dish
6. Power connections and communication
7. Touchpad and monitor

**Fig. 2.** Components of the portable near-infrared spectroscopy turntable system. 1, Functional unit; 2, turntable system; 3, power supply; 4, RFID readout unit; 5, Petri dish; 6, power connections and communication;7, touchpad and monitor.

sensor head was screwed precisely at the inner side of the channel and the cables were laid along the milling arm. The sensor head was adapted to the requirements of the agricultural machine. A sapphire crystal was used as a wear-free contact point to the silage, thus protecting against environmental influences such as temperature, air, water, dust and vibration. The sensor head has a redundant lighting unit in addition to an automatic and internal white referencing unit.

The NIRS functional unit was installed on the self-propelled feed mixer behind the driver's cabin. An oil-pressure gauge was integrated in the pressure line of the elevator drive and the miller to ensure a further communication between the NIRS function unit and feed mixer. The connected oil-pressure gauge indicates to the functional unit whether the miller is in operation.

At the beginning of the experiment, the NIRS system ran for the whole feeding process. Optimisation significantly reduced the number of measurements and then facilitated spectral evaluation. Two toggle switches, connected to the functional unit, were installed in the driver's cabin to match the measuring processes and ration ingredients. After completing the feeding process, the data were automatically transferred by insertion of a USB stick into the functional unit. The estimated values from DM and nutrients were averaged and stored with the associated milling operations.

Silage samples had to be taken during the milling process in order to check the installed NIRS system. This was necessary to improve the calibration models of grass and maize silages and subsequently to validate these models. The measurement, with sample number and substrate, was started. Configuration settings for the functional unit of the NIRS system mounted on the self-propelled feed mixer were 10 measurements with 1-s intervals. The measurement type was absorption and the exposure time was 18 ms.

### *Calibration models for grass and maize silages*

The calibration was aimed at integrating the NIRS system in the self-propelled feed mixers. For this purpose, a measurement device for calibration models for grass and maize silage was created. DM and nutrient contents were provided as parameters for these calibration models. The number of measurements of spectral image with the NIRS portable system was 244 for maize silage and 240 for grass silage, and for the NIRS mounted on the self-propelled feed mixer 225 for maize silage and 318 for grass silage.

The spectra and the reference analytical results were incorporated into the database and the calibration models were produced by means of special software created by m-u-t, Wedel, Germany. These models were calculated via the support-vector machine method (Cortes and Vapnik 1995).

### *Statistical analyses of data*

The data were analysed to determine the significant differences using SPSS version 22 (IBM, Armonk, NY, USA), where comparison of the mean values was made by one-way analysis of variance The statistical parameters for evaluating the calibration and regression models were carried out according to Tillmann (1996), Diller (2002) and Moschner (2007). The parameters were DM and nutrient contents for maize and grass silage, sampling positions, and validation models. For comparative evaluation of the models, the ratio performance deviation (RPD) value was used. A larger RPD value offers a better calibration for the prediction (François *et al*. 2009); a value <1.5 represents unreliable results, >2.0 indicates a suitable model and > 3.0 means the model shows an excellent prediction. Low standard error of cross-validation (SECV) and high $R^2$ are representative of a good calibration model (Park *et al*. 1999; Kański *et al*. 2013).

## Results

### *Silage analysis for dry matter and nutrient contents*

The variations between the two collected sample positions with respect to DM and other analysed nutrient contents for grass and maize silages are presented in Table 1. DM and nutrient contents in both the grass and maize silage silos were evaluated from collections at nine measurement points at the time interval of 7 days. For grass silage, the values of DM content varied between 19% and 54.4% with an average of 37.8% at P1 and varied between 24.4% and 47.5% with an average of 37.8% at P2. The average value of DM deviation between P1 and P2 was 6%. CP contents varied between 13.4% and 16.9% with an average of 15.6% at P1 and from 13.4% to 15.5% with an average of 14.7% at P2. The average deviation of CP between P1 and P2 was 1%. For maize silage, the DM content varied from 30.8% to 35.4% at P1 and from 26% to 36.7% at P2. The sample deviation between P1 and P2 was 2.3% DM.

**Table 1. Average ± standard deviation of dry matter (as a proportion of fresh matter) and nutrients (as a proportion of dry matter) for grass and maize silage silos with measurements at a 7-day interval**

P1, sampling at the surface of the silo; P2, sampling at the silo surface after 7 days extraction; nine samples from each silo were withdrawn at each sampling. $ADF_{OM}$, acid detergent fibre; $NDF_{OM}$, neutral detergent fibre

| Content (g/kg) | Sample position | Grass silage | Maize silage |
|---|---|---|---|
| Dry matter | P1 | 377 ± 95 | 333 ± 14 |
| | P2 | 387 ± 90 | 328 ± 34 |
| Crude ash | P1 | 115 ± 12 | 35 ± 2 |
| | P2 | 132 ± 18 | 33 ± 5 |
| Crude protein | P1 | 156 ± 12 | 98 ± 7 |
| | P2 | 147 ± 6 | 92 ± 4 |
| Crude fibre | P1 | 268 ± 20 | 188 ± 15 |
| | P2 | 261 ± 10 | 174 ± 23 |
| Crude fat | P1 | 41 ± 6 | 34 ± 3 |
| | P2 | 41 ± 5 | 39 ± 4 |
| Sugars | P1 | 35 ± 35 | – |
| | P2 | 27 ± 32 | – |
| Starch | P1 | – | 309 ± 104 |
| | P2 | – | 338 ± 26 |
| $ADF_{OM}$ | P1 | 287 ± 14 | – |
| | P2 | 282 ± 13 | – |
| $NDF_{OM}$ | P1 | – | 403 ± 78 |
| | P2 | – | 353 ± 28 |

### *Wet chemical reference analyses*

The results from wet chemical analyses showed variations of the parameters of grass and maize silages during the whole year (Table 2). The respective values of DM, CA, CP, CF and CE averaged 39.7%, 13.8%, 15.2%, 24.8% and 3.7% for grass silage and 34.8%, 3.9%, 8.6%, 18% and 3.6% for maize silage. Sugar content and $ADF_{OM}$ averaged 3.4% and 26.3% for grass silage; starch content and $NDF_{OM}$ averaged 33.3% and 36.8% for maize silage. Rumen nitrogen balance was 3 g N for grass silage and –8 g N for maize silage.

### *Calibration of grass and maize silage model parameters*

Calibration models for grass and maize silages were created and transferred to both the portable NIRS turntable system and the NIRS system mounted on the self-propelled feed-mixer wagon. In this study, the term 'offline' refers to the portable NIRS turntable system and the term 'online' to the NIRS system mounted on the self-propelled feed-mixer wagon. In the final validation, unknown samples were measured with the offline and online systems and the estimated results from NIRS were then compared with the reference analysis results. The linear regressions of DM and CP content for the grass and maize silage models are illustrated in Fig. 3; for each graph, the dotted straight line passes through the origin and indicates congruence of the individual values of the wet chemical reference value and the NIR measured value. The solid line describes the regression function.

The span of calibration of the grass silage samples was 21.3–59.2% DM content. In this area, a prediction of the DM contents is relatively accurate. The span of the calibration of the maize silage samples was 26–46.7% DM content. A prediction of the DM contents in this area is also relatively accurate. The CP content had a span value of 11.4–18.3% for the grass silage model and 5.4–10.8% for the maize silage model.

**Table 2. Wet chemical analysis for both grass and maize silage samples**
s.d., standard deviation; DM, dry matter; FM, fresh matter; CP, crude protein; CA, crude ash; CF, crude fibre; CE, crude fat; HFT, Hohenheim feed test (*in vitro* gas-production technique); $ADF_{OM}$, acid detergent fibre; $NDF_{OM}$, neutral detergent fibre; uCP, usable crude protein; RNB, rumen nitrogen balance

| Content | Grass silage | | Maize silage | |
|---|---|---|---|---|
| | *n* | Average ± s.d. | *n* | Average ± s.d. |
| DM (g/kg FM) | 194 | 397 ± 109 | 142 | 348.25 ± 37.80 |
| CA (g/kg DM) | 192 | 138 ± 31 | 139 | 39.83 ± 18.78 |
| CP (g/kg DM) | 192 | 152 ± 14 | 142 | 85.87 ± 18.00 |
| CF (g/kg DM) | 192 | 248 ± 18 | 142 | 180.33 ± 22.31 |
| CE (g/kg DM) | 185 | 37 ± 7 | 142 | 35.96 ± 8.75 |
| Sugars (g/kg DM) | 185 | 34 ± 34 | – | – |
| Starch (g/kg DM) | – | – | 142 | 332.61 ± 47.52 |
| HFT (mL/200 mg) | 132 | 59 ± 60 | – | – |
| pH | 185 | 4.4 ± 0.3 | 140 | 3.67 ± 0.22 |
| $NH_3$-N (%) | 185 | 7.96 ± 2.05 | 142 | 3.19 ± 1.59 |
| $ADF_{OM}$ (g/kg DM) | 178 | 262 ± 30 | | – |
| $NDF_{OM}$ (g/kg DM) | – | – | 142 | 367.79 ± 39.43 |
| uCP (g/kg DM) | 131 | 130 ± 6 | 142 | 138 ± 8 |
| RNB (g N) | 131 | 3 ± 2 | 142 | –8 ± 2 |

The statistical parameters for the evaluation of calibration and regression models are summarised in Table 3 for the grass and maize silage samples. From the illustrated quality parameters, the root-mean-square error of cross-validation (RMSECV), the RPD (RMSECV), systematic error (BIAS) and the standard error of cross-validation (SECV) are particularly important. The values for RMSECV varied between 1.47% and 0.40% for grass silage samples and between 1.28% and 0.36% for maize silage samples. The RPD values were similar for both grass and maize samples, with RPD in the range 1.3–1.67 for the grass silage and 1.21–1.61 for maize silage. The BIAS values were in the range 0.31–1.15% for the grass silage and from 0.28–1.02% for maize silage. The respective SECV values for CA, CF and CE were 1.03%, 0.62% and 0.28% for the grass silage and 1.79%, 1.53% and 0.77% for the maize silage. In summary, the results for grass and maize silage parameters with an RMSECV of <1.5% were very satisfactory.

### *Validation and monitoring the NIRS systems*

The samples for the grass and maize silage models were randomly measured during feed extraction with the self-propelled feed mixer. The same samples were then re-measured with the sensor on the feed mixer wagon. Both were included in the online and offline validation. Table 4 summarises the validation of the grass and maize silage models for the online and offline systems, and Fig. 4 shows the linear regression of DM content for both grass and maize silages with the online and offline systems.

For the portable NIRS rotary turntable system (offline) with grass silage, the validation covered a range of 26.6–56.1% for DM content with 2.1% mean absolute deviation (MAD) and 2.26% standard deviation (s.d.). With maize silage, the validation covered a range of 26.2–37.7% for DM content, with a MAD value of 0.9% and s.d. of 1.1%. Fourteen of 16 samples were within a tolerance range of ±2% DM content.

For the NIRS system mounted on the self-propelled feed mixer (online) with grass silage, the validation covered the range of 26.6–56.1% for DM content. The MAD value was 2.6% and the s.d. was 2.96%. With maize silage, the validation covered the range of 26.8–37.7% for DM content with a mean of 34.7%; the results of the NIR measurements gave a range of 29.1–37.2% for DM and a mean of 34.3% with a MAD value of 1.6% and s.d. of 1.8%. The regression model had an $R^2$ of 0.61. Twenty of the 28 samples were within a tolerance range of ±2% for DM content, and the remainder were within a tolerance range of ±1% deviation. The MAD between NIR measurement and wet chemical analysis was 0.6% for CP content for the offline system and 0.8% for CP content for the online system. The s.d. values for both systems were <1%. Results for other nutrients content such as CA, CF and CE for grass and maize silages were also summarised in Table 4.

## Discussion

### *Evaluation of the sample material*

For DM calibration of the grass silage, the samples had an average of 37.1% of the fresh matter (FM). According to

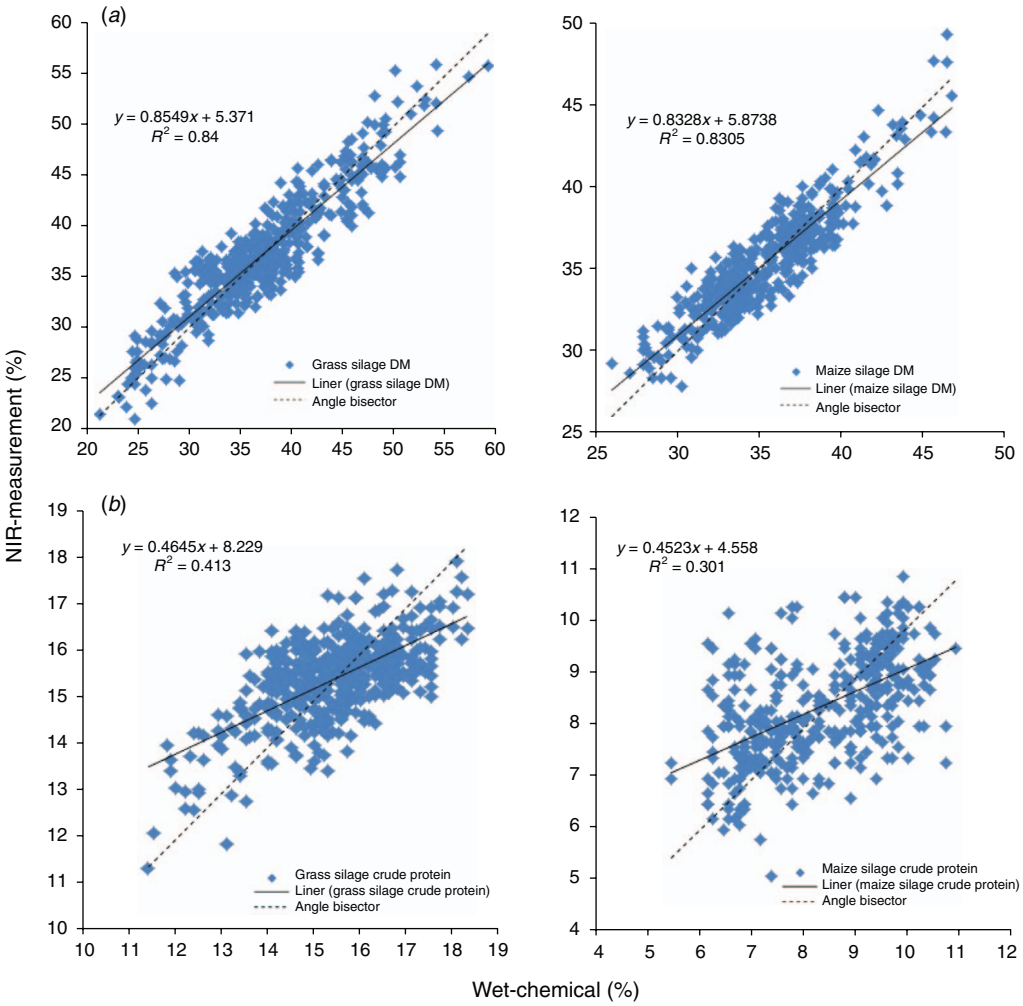



**Fig. 3.** Calibration of grass and maize silage models: linear regression of dry matter and crude protein contents.

**Table 3. Calibration for dry matter (DM) and nutrient contents of grass and maize silages**

RMSECV, root-mean-square error of cross-validation; RMSEC, root-mean-square error of calibration; RPD, ratio performance deviation, standard deviation of the reference data to the root-mean-square error of prediction; SECV, standard error of cross-validation; BIAS, system error; FM, fresh matter; CP, crude protein; CA, crude ash; CF, crude fibre; CE, crude fat

| Content | RMSECV | | RMSEC | | RPD (RMSECV) | | SECV | | BIAS | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Grass | Maize | Grass | Maize | Grass | Maize | Grass | Maize | Grass | Maize |
| DM (% of FM) | 2.44 | 1.46 | 2.07 | 1.17 | 2.53 | 2.43 | 2.81 | 1.04 | 1.93 | 1.19 |
| CP (% of DM) | 0.97 | 0.92 | 0.59 | 0.79 | 1.30 | 1.36 | 0.62 | 1.38 | 0.81 | 0.71 |
| CA (% of DM) | 1.47 | 0.36 | 1.33 | 0.30 | 1.53 | 1.21 | 1.03 | 1.79 | 1.15 | 0.28 |
| CF (% of DM) | 0.92 | 1.28 | 0.66 | 1.09 | 1.67 | 1.12 | 0.62 | 1.53 | 0.74 | 1.02 |
| CE (% of DM) | 0.40 | 0.37 | 0.30 | 0.31 | 1.32 | 1.61 | 0.28 | 0.77 | 0.31 | 0.303 |

Spiekers *et al*. (2009), the DM content of grass silage should not exceed 40% of the FM, to avoid compaction problems. Thus, a large portion of the samples was within the expected measuring range. Because the contents of grass silage are weather-dependent and this can often lead to strong variations, the measuring range of the model for DM in the grass silage was 21–59% of the FM and the average DM content for the maize silage was 35.2% of the FM. Several authors (Spiekers *et al*. 2009; Kleinmans *et al*. 2016) have indicated that the DM content should be within the range of 32–35% for the whole maize plant, and therefore, the results reported in this study are slightly above the recommended range.

The CP contents of grass silage, with an average of 15.2% of the DM, matched those reported by Hall and Mertens (2012)

**Table 4. Validation of the grass and maize silage models**

Offline, the portable NIRS turntable system; Online, the NIRS system mounted on the self-propelled feed-mixer wagon; MAD, mean absolute deviation; s.d., standard deviation; DM, dry matter; FM, fresh matter; CP, crude protein; CA, crude ash; CF, crude fibre; CE, crude fat

| Content | System | Reference method | | NIR measurement | | MAD | | s.d. | |
|---|---|---|---|---|---|---|---|---|---|
| | | Grass | Maize | Grass | Maize | Grass | Maize | Grass | Maize |
| DM (% of FM) | Offline | 37.5 | 34.9 | 36.5 | 34.7 | 2.1 | 0.9 | 2.3 | 1.1 |
| | Online | 36.8 | 34.7 | 37.1 | 34.3 | 2.6 | 1.6 | 3.0 | 1.8 |
| CA (% of DM) | Offline | 14.2 | 4.1 | 12.2 | 3.7 | 2.7 | 0.6 | 3.4 | 0.9 |
| | Online | 14.3 | 4.1 | 11.9 | 3.6 | 2.9 | 0.5 | 3.7 | 0.8 |
| CP (% of DM) | Offline | 12.8 | 7.5 | 13.8 | 7.1 | 1.2 | 0.6 | 1.2 | 0.5 |
| | Online | 12.8 | 7.5 | 13.5 | 7.2 | 1.4 | 0.8 | 1.6 | 0.9 |
| CF (% of DM) | Offline | 27 | 18.4 | 25.6 | 18 | 1.7 | 1.0 | 1.5 | 1.3 |
| | Online | 26.9 | 18.6 | 24.5 | 18.1 | 2.6 | 1.0 | 1.5 | 1.4 |
| CE (% of DM) | Offline | 3.2 | 3.8 | 3.6 | 3.5 | 0.5 | 0.4 | 0.5 | 0.2 |
| | Online | 3.2 | 3.8 | 3.2 | 3.5 | 0.6 | 0.4 | 0.7 | 0.3 |

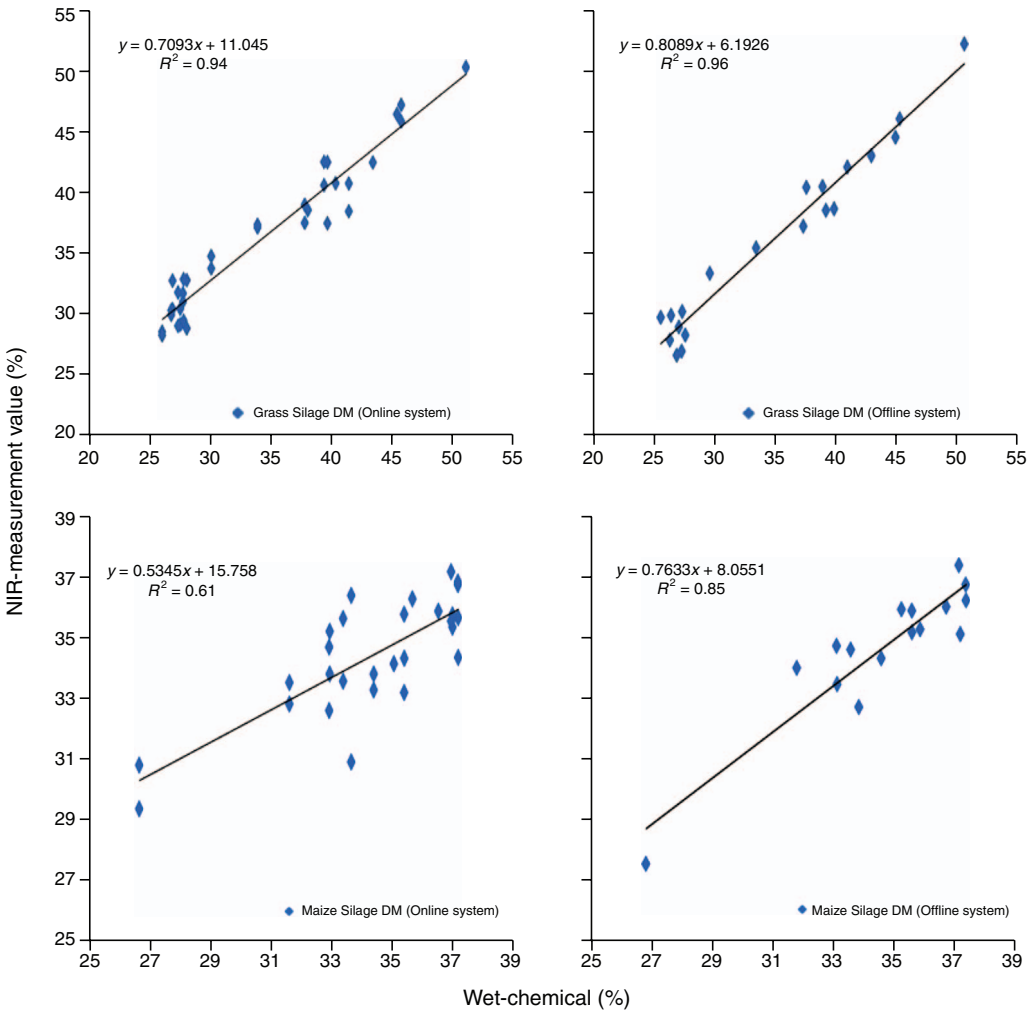



**Fig. 4.** Validation of the investigated models: linear regression of dry matter content.

and very close to those obtained by Kleinmans *et al*. (2016) and Marchesini *et al*. (2018). On the other hand, the CP content of the maize silage showed an average of 8.3% of the DM, which is less than the CP of the grass silage but similar to results reported by Hall and Mertens (2012) and Petrovska *et al*. (2015).

The CA content of grass silage showed an average of 13.8% of the DM. For calibration, the CA content should be kept at a

minimum of 4% of the DM. According to Spiekers and Attenberger (2009), the target value of CA should be <10% of the DM. The higher values reported in this study could be due to soil contamination of feed. Cherney *et al*. (1983) reported that contamination of silage by soil negatively impacts analysis results. Thus, calibration of CA content for the grass silage presents a special challenge. On the other hand, the CA content of the maize silage averaged 3.5% of the DM. The required target value is <4.5% of the DM as recommended by Spiekers and Attenberger (2009).

The results of CF (24.6% of DM) and CE (3.8% of DM) contents for grass silage are similar to those reported by Spiekers and Attenberger (2009). The average CF content of the maize silage was 17.8% of the DM, which was similar to that reported by Spiekers and Attenberger (2009). The average CE content of the maize silage was 3.5% of the DM.

The fibre content in silage is linked to feed intake and digestibility and, subsequently, animal production (Kumar *et al*. 2016). Fibre content for good silage is in the range 17–20% of the DM for maize silage and 22–25% for grass silage as reported by Spiekers *et al*. (2009). Therefore, the results illustrated in Table 2 refer to good-quality silage. Fibre content comprises some compounds such as ADF and NDF. Increasing ADF reduces feed digestibility, and feed intake declines with increasing NDF in the silage (Kumar *et al*. 2016). Most of the CP for the silage is degraded, which is known as rumen-degradable protein. The study showed adequate rumen-degradable protein for the investigated silages according to Spiekers *et al*. (2009). Thus, the content of grass and maize silage in terms of a balanced rumen-degradable protein is suitable to sustain microbial activities and, subsequently, rumen digestibility.

### *Evaluation of the NIR systems*

The NIRS system was used to create the estimation models and their validation was developed for outdoor use. This means that the method of development had to be adapted to the environmental conditions. Thus, when comparing the results with those reported in the literature, differences in the measurement conditions should be considered. Previous studies reported in the literature have been performed with dried silage or fresh material and the measurements took place under laboratory conditions. The NIRS system mounted on a self-propelled feed-mixer wagon has not yet been scientifically investigated.

#### *Portable NIRS turntable system*

Development of the portable NIRS turntable system made it possible to create the first calibration models for grass and maize silages. Direct use of the portable measuring technology on the farm allowed the samples to be measured quickly, as well as allowed handling of high sample volumes. Rotation of the sample to be measured above the sensors created an accurate representation. Sampling via the sample drill made it possible to obtain a high variance of the DM and nutrient contents. The system can now be used to determine DM and nutrient contents. This quick and non-destructive method can be used for scientific experiments in the future.

#### *NIRS system mounted on the self-propelled feed mixer*

The NIRS system was adjusted to the requirements of mobile agricultural machines. The installation of the NIRS system on the self-propelled feeder mixer had to be done without major changes of the machine, because there was little space for modifications. The installation of the NIR sensor head in the milling arm positions it in a relatively safe place, largely protected against external influences. This position offers the possibility of continuously measuring the substrates and indicating a representative prediction of DM and nutrient contents.

The milled substrates reach the sensor in large amounts. Owing to the high speed of the milling drum, the feed is pushed through the measuring window, and thus, few incorrect measurements could occur. A self-cleaning effect was observed, due to the high speed of the material. The cable entering the sensor head, which ran along the milling arm and the elevator belt, was protected by metal covers. This could theoretically be integrated into the elevator shaft, but would be difficult to reach for repairs.

The current location for the functional unit, mounted on the self-propelled feed-mixer wagon, still needs to be modified for series production because it is not fully accessible behind the driver's cabin. The size of the outer housing of the functional unit can be further reduced for better meeting the space requirements on the feed-mixer wagon.

### *Evaluation of calibrations and validations*

For evaluation of the calibration, the reference values for the comparison with other results of RMSECV, RMSEC (root-mean-square error of calibration), RPD (RMSECV) and SECV were used. The RPD value (quotient of the s.d. of the reference values of the validation samples and the standard error of the prediction) is a dimensionless variable used to facilitate the comparison of the NIRS methods for DM and nutrients. The method development for the models was established for the prediction of the DM and nutrient contents directly at the feed intake on the self-propelled feed mixer. Therefore, the validations of the individual models have a particular interest because they can contribute to the optimisation of the feed ration. Deviations of absolute values for individual parameters must be in the lowest possible range, so that they can be used for optimisation. The MAD and s.d. of the wet chemical reference value and the NIR measured value were compared. The DM and CP content of the grass and maize silage models were evaluated, because these are the factors of most influence in ration optimisation.

#### *Calibration and validation of grass silage*

The RPD (RMSECV) value of the calibration model for DM prediction in undried grass silage achieved a moderate quality and the prediction performance was satisfactory (Williams 2014). With a low SECV (Table 3) and a high $R^2$ (Fig. 3), the model represented good results as suggested by Kański *et al*. (2013). The RMSEC value reported by Abrams

*et al*. (1988) was 1.8%, and the RMSECV value reported by Kennedy (1996) was 1.2%.

In the online–offline validation of DM, the levels are in line with the previous studies reported by Wild and Kormann (2007). The RPD (RMSECV) value for the CP of the grass silage (1.30) means that the system is not recommended for use according to Williams (2014).The RMSECV, RMSEC and SECV are consistent with the results reported by Downey *et al*. (1989) for CP of dried grass silage. Kennedy (1996) reported an RMSECV of 1.16% DM for grass silage measured in laboratory and 1.93% DM for fresh grass. De Boever *et al*. (1996) reported an RMSECV of 0.6% FM and SECV of 0.8% FM for dried grass silage. Heinrich *et al*. (2005) reported an SECV of 1.25% FM of grass in a laboratory-scale experiment. The CP content measurements are between the deviation from the wet chemical reference value and the NIR measured value.

### *Calibration and validation of maize silage*

The calibration model for predicting the DM content of undried maize silage is illustrated in Table 3. The RPD (RMSECV) value showed a suitable calibration model according to François *et al*. (2009). The regression model obtained has an $R^2$ of 0.8, which is similar to values reported by Park *et al*. (2005) and Marchesini *et al*. (2018). This high regression coefficient reflects the high predictability of the model as stated by Kański *et al*. (2013). The obtained SECV value was lower than values reported by Park *et al*. (2005) and Marchesini *et al*. (2018). However, the results showed a highly accurate prediction according to Kański *et al*. (2013). The RPD (RMSECV) value for the CP of the maize silage means that the system is not recommended for use according to Williams (2014), although the results from this investigation showed an RMSECV of 0.92% and RMSEC of only 0.79%.

### *Factors influencing the NIRS measurements*

Images of the spectra for the calibration and validation of the grass and maize silage models were not conducted as in other laboratory studies where the measurements can be performed under standardised conditions. The advantages of laboratory work are the repeatability of sample measurements with the possibility of controlling the surrounding conditions. Furthermore, samples in the laboratory always have the same orientation to the light source and the detector. All of these conditions could not be guaranteed in the tests performed outdoors or on the self-propelled feed-mixer wagon. Accordingly, the accuracies of the field study could not be directly compared with the accuracies of laboratory NIR measuring instruments. Therefore, while recording spectra using the NIRS portable turntable system and NIRS system mounted on the self-propelled feed-mixer, various sources of error could influence the results, as reported by Park *et al*. (2005).

The deviations from the absolute values depend on several factors including sample preparation, sample presentation, the variance of the measuring instruments, and the laboratory analysis. The spectral images with the portable NIRS turntable system were protected from light radiation by a cover; thus, no stray light could lead to changes. However, the spectral images on the feed-mixer wagon were not completely protected, which could lead to incorrect measurements due to light irradiation. Another problem could be the variation in the amounts of feed on the sensor head. A large quantity of feed on the glass surface could over-compact the feed and cause different reflections. In addition, the feed components always have a different angle to the light source and the detector. These factors can result in increasingly random errors in the online measurements.

The way of presenting the sample in front of the NIR sensor is particularly critical for calibration accuracy, as stated by Williams (2014). In the study by Wild and Kormann (2007), the NIR sensor heads were mounted on a forage-harvester deflector. The advantage of this type of spectral recording is that incorrect measurements due to the light effect can be avoided. The relatively narrow area of the deflector offers good possibilities to allow enough material to pass through the sensor head.

For preparation of the calibrations and validations, the samples were frozen for wet chemical analysis. Errors could have occurred during the analyses as a result of thawing or drying of the samples, which in turn is reflected in the calibration. The type and duration of the measurements could also influence the accuracy of measurements. The better accuracy of the portable NIRS turntable system than the NIRS system mounted on the feed mixer is due to the way of representing the measurement samples. For the portable NIRS turntable system, the samples were rotated for ~60 s around the sensor head. Accordingly, a large part of the sample composition could be detected. For the measurement on the mixing wagon, the reference sample took ~1 s, a much lower presence. The chop length of the grass silage also has an effect on the accuracy of the calibration, as indicated by Reeves and Blosser (1991) and Park *et al*. (2005).

## Conclusions

The main goal of the study was to devise an approach for estimating DM and nutrient contents during silage extraction from silos and thus improve the total mixed ration. An NIR system was successfully used to achieve this research target. The system was used as a portable turntable and was also mounted on a self-propelled feed mixer. The NIR measurement technology and the accuracy of the calibration models were assessed. Where the silage is considered as inhomogeneous material, the NIR-technique made sense with the determination of DM and nutrients content of stored silage. Therefore, the NIR-technique was sufficiently accurate for DM and nutrients estimations that allowed adjustment of the daily ration.

Consequently, NIRS is a suitable method for measuring DM and nutrient contents continuously during feed extraction from the bunker silo. The recorded spectra of the NIRS system as ran under standardised conditions at the laboratory scale using a portable turntable system was much more accurate than when it was installed on the self-propelled feed mixer. This could be the result of various influencing factors in the field experiment such as light radiation, temperature and vibrations, which can cause measuring errors.

The calibration achieved a moderate quality, and the prediction performance was satisfactory. Accordingly, the models can contribute towards optimising the ration. Optimisation of the reference sample number over the whole measurements is recommended in order to improve the grass and maize silage models.

## Conflicts of interest

The authors declare no conflicts of interest.

## Acknowledgements

This research project was funded by the Federal Office for Agriculture and Food (Bundesanstalt für Landwirtschaft und Ernährung). The support provided by the companies B. Strautmann & Söhne GmbH u. Co. KG and m-u-t GmbH is highly appreciated.

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Handling editor: Karen Harper