



Review article

## Near-Infrared Spectroscopy (NIRS): Its Use in the Evaluation of Animal Feed Alternative

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### ABSTRACT

**Background:** Near-infrared spectroscopy (NIRS) is based on the interaction between matter and infrared radiation adjacent to the visible spectrum. Since the 1970s, NIRS has been employed to predict nutritive components of animal feeds. **Objective.** To provide an overview of the characteristics of NIRS and its application to the evaluation of animal feed. **Development:** The first significant application of NIRS to animal-feed evaluation was reported in 1976. Its use has increased markedly owing to its speed, non-destructive nature, and favorable cost-effectiveness. Advances have been driven in large part by the integration of relatively sophisticated procedures for handling large datasets, since predictive statistical models obtained during calibration are required. A diverse set of samples that spans the full range of expected variation in the parameters of interest must be collected. The model is then validated with an independent sample set with known reference values, which permits assessment of performance using statistics such as the coefficient of determination and the standard error of prediction. **Conclusion:** NIRS represents one of the most significant spectroscopic advances of recent decades. In animal production it can be used for feed quality grading, feed formulation, and verification of final product quality. **Keywords:** animal feed; spectroscopy; regression models; near-infrared spectroscopy (NIRS) (*Source: AIMS*).

### INTRODUCTION

Instrumental analytical techniques exploit physical properties that are, in some manner, related to the analyte. Optical spectroscopy is founded on the interaction between the substance under analysis and electromagnetic radiation; this interaction may involve emission, absorption, or both. The radiation may be visible, ultraviolet, or infrared, depending on the wavelength range

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considered. Near-infrared spectroscopy (NIRS) examines spectra in the wavelength range from 900 to 2500 nm (Amaral, 2022).

Since the 1970s, NIRS has been employed to predict nutritive components of animal feeds (Norris *et al.*, 1976). Recent advances now enable *in-situ* analysis of silages, grains, and compound feeds, thereby reducing reliance on laboratory methods that require lengthy turnaround times and are more environmentally intrusive (Bristy *et al.*, 2025).

This paper aims to provide an overview of the characteristics of near-infrared spectroscopy (NIRS) and its application to the evaluation of animal feed.

## DEVELOPMENT

By virtue of the spectral region in which the interaction occurs, it primarily affects the covalent bonds in organic matter involving elements such as carbon, nitrogen, oxygen, and hydrogen. Correlations have also been observed between the spectra and other elements, including phosphorus and sulfur, as well as certain metals bound to organic matter (Zhang *et al.*, 2022).

The method can be rapid and non-destructive when the spectrum is acquired by reflectance of incident light from the intact sample (Kun-Jun, 2023). According to Ibrahim *et al.* (2023) and Maduro *et al.* (2024), the technique provides operational and economic advantages that are unmatched by conventional methods in applications where speed and non-destructiveness are critical.

The absence of chemical residues in NIRS not only lowers laboratory waste-disposal costs but also mitigates regulatory risks (Jun *et al.*, 2023; Mendoza *et al.*, 2023; Xu *et al.*, 2024).

### How to operate NIRS

All instrumental analytical methods require prior calibration (a correlation between the measured property and the analyte concentration) before measurements are performed. NIRS is no exception.

To achieve reliable results, it is crucial to collect a diverse set of samples that encompass the full range of expected variation in the parameter of interest (Murphy *et al.*, 2022).

Near-infrared (NIR) spectra are acquired for each sample to generate spectral data. These samples must be analyzed by conventional reference methods (e.g., HPLC, Kjeldahl, Van Soest) to obtain accurate values that serve as calibration data for determining their true properties. High-quality reference values are essential for developing robust calibration models (Catunda *et al.*, 2022; Murphy *et al.*, 2022; Si-Ware, 2024).

The particle size influences light scattering, which can alter the intensity and shape of the NIR spectrum. Very large particles may cause excessive scattering, whereas very small particles can yield more uniform absorption but with lower signal intensity. More important than any specific particle size is maintaining a uniform particle-size distribution across all samples used for calibration. This minimizes spectral variability due to scattering and ensures that predictive models are robust and accurate (Hossain *et al.*, 2024). In some cases, such as food analysis, particle size must be adjusted to comply with standards. Moreover, NIRS can be adapted to operate with different particle sizes, but adequate control during calibration is always required (Murphy *et al.*, 2022; Hossain *et al.*, 2024).

Given the volume of data to be handled (a single spectrum from 900 to 2500 nm sampled at 1-nm intervals yields 1600 values), the use of powerful mathematical methods is essential.

### **Mathematical processing**

Multiple linear regression is rarely used because it cannot adequately handle complex datasets (Han *et al.*, 2022). NIR spectra contain a large number of variables (wavelengths) that may be correlated. Principal component regression (PCR) helps identify the principal components that capture the greatest variability in the data, thereby reducing the dimensionality of the dataset. This facilitates analysis and interpretation by focusing on the variables most relevant to the parameter of interest (Si-Ware, 2024).

Chemometrics is applied to paired spectral and reference data to determine how specific spectral features correspond to the properties of interest. To improve signal quality, spectral data preprocessing is essential to remove noise, scattering, and baseline drift. Common preprocessing methods include: (i) first and second derivatives, which enhance subtle differences by emphasizing changes in slope; (ii) variable standardization, which corrects changes due to differences in particle size; and (iii) orthogonal signal correction, which removes irrelevant variations unrelated to the property under study (Jun *et al.*, 2023).

Partial least squares regression (PLS) is widely used in NIRS because of its ability to handle multicollinear data and to capture relationships between spectral and chemical variables. It is particularly effective when a linear relationship exists between the spectra and the properties to be determined (Maduro *et al.*, 2024), which occurs quite frequently.

Although both PCR and PLSR are effective methods for NIRS calibration, PLSR tends to be more commonly used because it can directly incorporate information about the dependent variable into the component-selection process. PCR, however, is useful when a more detailed understanding of the spectral-data structure is desired prior to regression (Maduro *et al.*, 2024), since it mitigates multicollinearity by transforming the original variables into principal components that are orthogonal to one another. This transformation reduces instability in parameter estimation, which can be problematic in traditional multiple regression. Variable

reduction and the elimination of multicollinearity contribute to greater model stability; coefficient estimators then have lower variance, thereby improving prediction accuracy (Catunda *et al.*, 2022; Xu *et al.*, 2024).

The model is tested with an independent set of samples with known reference values. This allows its performance to be evaluated using statistics such as the coefficient of determination ( $R^2$ ) and the standard error of prediction (Si-Ware, 2024). Cross-validation can be carried out by working with small groups of data that are left out of the model in each iteration (Skvaril *et al.*, 2025).

Local and global models have been developed to accommodate different types of samples and products (Reddy *et al.*, 2023). Local models are useful when a database specific to a sample type is available, whereas global models are more versatile but require more robust calibration (Hossain *et al.*, 2024).

The development of NIRS as a viable analytical technique has been closely tied to the modernization of the infrastructure for capturing spectra (diode arrays, interferometers, and Fourier transform) and to the processing of the information these provide in relation to sample characteristics. Both have depended on increases in microcomputer power (Gomez *et al.*, 2024).

### **Limitations**

It is not the method of choice for trace-level analytes, such as mycotoxins and other components present at very low concentrations in foods. NIRS requires minimum concentrations of about 100 ppb, whereas HPLC-MS (high-performance liquid chromatography coupled with mass spectrometry) can detect down to 1 ppb (Maduro *et al.*, 2024).

Although its possible use has been tested (Campos, 2015), in the evaluation of metals—particularly those in ionic (electrolytic) form—good correlations with the NIR spectrum are only achieved when the metals are bound to organic matter.

The specificity of models and their dependence on local conditions make cross-laboratory validation difficult. Calibration transfer between instruments increases error, a problem that remained largely unresolved in most models until recent years (Fan Wei, 2021). To correct the bias introduced between instruments, some proposed solutions include common blockchain-based databases and machine-learning approaches to harmonize global data (Evans, 2021).

Recent studies (Castillo *et al.*, 2025) show that, at times, inconsistencies appear in the accuracy of predicted values, highlighting the need for more robust validations. They recommend using visual tools—such as scatter-plot analyses comparing laboratory measurements with predicted values—to achieve better data assessment.

### **Uses in food evaluation**

The first significant use of NIRS in animal feed evaluation was reported in 1976, related to the prediction of *in vivo* and *in vitro* digestibility of forages (Norris *et al.*, 1976). The authors demonstrated NIRS's ability to accurately predict dry-matter digestibility. In the 1970s, advances in instrumentation—particularly in monochromators—improved the precision of spectral analyses, which facilitated the prediction of protein and fiber content in forages. During the 1980s and 1990s, NIRS expanded to include analyses of raw materials and compound feeds, enabling evaluation of protein, fat, and starch content in mixed feeds (Barber *et al.*, 1990). The subsequent development of chemometrics further broadened the technique's scope (Rodríguez-Hernández *et al.*, 2023; Hossain *et al.*, 2024). The technique has also been used to predict energy content in pet foods (Hervera *et al.*, 2012).

In general, near-infrared spectroscopy has since become and remains a transformative tool in food evaluation, characterized by being non-destructive, fast, and relatively inexpensive for analyzing nutritional parameters (Santos *et al.*, 2022; Bagavan *et al.*, 2023). Near-infrared spectroscopy has transformed animal production by significantly improving efficiency and cost-effectiveness in several key areas. Below are some relevant impacts:

NIRS enables rapid analysis of the nutritional content of forages and feeds, facilitating the formulation of more precise and efficient rations and timely decision-making (Nipane *et al.*, 2023). This reduces feeding costs by adjusting nutrient amounts to the specific needs of the animals, which—for example—can lower ration costs on dairy farms by 5–10% (Pereira-Crespo, 2021).

By replacing traditional chemical analysis methods, NIRS reduces costs associated with sending samples to external laboratories and the use of chemical reagents. In addition, portable devices enable on-site analyses, minimizing dependence on external services and improving internal quality management (Garrido, 1996; Alessandro *et al.*, 2025; Yadav *et al.*, 2025).

The ability of NIRS to provide rapid results (in a matter of seconds) allows producers to adjust their feeding and production strategies in real time. This is particularly useful for responding to changes in climate, ingredient prices, or forage quality (Garrido, 1996; Amaral, 2022; Garcia and Flanagan, 2024). It can be effective even in applications where variability is large, such as meat analysis (Lizárraga-Hernández, 2021; Xu *et al.*, 2024).

By optimizing ration formulation, overfeeding is reduced and, consequently, nutrient excretion to the environment decreases. This contributes to a lower environmental burden and a more efficient use of natural resources (Pereira-Crespo, 2021; Reddy *et al.*, 2023).

In some cases, the specificity of the type of sample to be analyzed is important.

For forages, a special approach is required to predict parameters such as dry matter, crude protein, neutral detergent fiber, and *in vitro* digestibility (Pereira-Crespo, 2021; Alessandro *et al.*,

2025), whereas for compound feeds the calibration must cover a wide range of ingredients and nutrients and focuses on predicting protein, moisture, and other nutrients essential for the finished product (Bagavan *et al.*, 2023; Yadav *et al.*, 2025).

### **Recent advances**

Portable devices enable *in-situ* analysis of silages, grains, and compound feeds, reducing reliance on methods that take time to produce results. Integrating NIRS with software platforms allows efficient storage and management of calibration curves and prediction equations. This helps reduce data variability and improves result accuracy by correlating them with existing wet-chemistry and traditional spectral analyses (Bristy *et al.*, 2025).

Modern algorithms such as artificial neural networks (Bandyopadhyay *et al.*, 2025), and support vector machines, enable the system to handle nonlinear relationships between spectral data and chemical properties. Nonlinear calibration techniques like kernel regression (Zhang *et al.*, 2022) and ridge regression (Huang *et al.*, 2024) can be used. Good models can be obtained with data that have wide variability, but they require large volumes of data and substantial computational power for training (Maduro *et al.*, 2024).

Support vector machines are effective for classification and nonlinear regression problems. In NIRS, they can be useful for modeling complex relationships, although they require careful parameter selection (Workman, 2025; Wang *et al.*, 2025).

In the last five years, NIRS has been integrated into precision livestock systems to monitor feed quality in real time. Portable devices enable *in-situ* analysis of silages, grains, and compound feeds, reducing dependence on laboratories that require more time (Han *et al.*, 2022; Candelaria-Carbajo, 2023).

More recently, NIRS has also been applied to authenticate food ingredients and detect contaminants. For example, it has been used to distinguish between pasture-based and concentrate-based diets by analyzing milk and fecal samples (Han *et al.*, 2022; Rodríguez-Hernández *et al.*, 2023). Its ability to predict biologically meaningful parameters such as metabolizable energy with very good accuracy has also been demonstrated (Hossain *et al.*, 2024; Huang *et al.*, 2024).

The future of NIRS in animal feed evaluation rests on its integration with big-data analyses and machine-learning algorithms to create global models that remain robust across different feed types. Procedures enhanced by the rise of artificial intelligence techniques such as deep learning have expanded NIRS's role into image processing. (Wang *et al.*, 2025; Workman, 2025).

## Use of NIRS in Cuba

In Cuba, the main focus has been on the production and management of pastures and forages, with an emphasis on fertilization and crop yield. Not many specific studies on the use of NIRS in the country have been found; however, the technique is recognized for its speed, reliability, and low cost, making it ideal for implementation in animal nutrition programs (Valenciaga and Olivera, 2006; Estupiñán *et al.*, 2021).

## At the University of Camaguey

Currently, thanks to the participation of the University of Camaguey in PROLAIF, there is equipment available at the animal feed evaluation laboratory. The concentrations of the indicators to be measured are calculated using calibrations from CIRAD in France, and efforts are underway to eventually develop our own calibrations.

## CONCLUSIONS

NIRS is likely the most advanced optical spectroscopy of the past decades. When used properly, it is the ideal technology for rapid analyses. In animal production it can be used for grading feed quality, formulation, and verifying the quality of the final product. No special skills or sample preparation are required; the instruments are easy to operate and results are available immediately. Calibration development, and especially programs to maintain an appropriate calibration, are essential to ensure continuously reliable results and require adequate laboratory infrastructure.

Some steps have been taken in Cuba in the use of this analytical technology, and work is currently underway to go further and consolidate those advances.

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### **AUTHOR CONTRIBUTION STATEMENT**

Research conception and design: SJMS, CAOG, MLG; data analysis and interpretation: SJMS, CAOG, MLG; manuscript writing: SJMS, CAOG, MLG.

### **CONFLICT OF INTEREST STATEMENT**

The authors state there are no conflicts of interest whatsoever.