Near Infrared Reflectance Analysis as a Method to Measure Metabolizable Energy in Complete Poultry Feeds

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ABSTRACT Near infrared reflectance analysis (NIRA) was assessed as a potential technique to measure metabolizable energy (AME_n) in complete poultry feeds. Eighty poultry feeds (for layers, broilers, and turkeys), with known AME_n values (range; 2.120 to 3.553 kcal/g), were used in the present study. Twenty different ingredients were used in the formulation of the diets. A total collection procedure was used in obtaining the AME_n values (a 3-day adaptation period and a 4-day collection period). From the 80 feeds, 49 were used to develop the NIRA calibration for AME_n and the remaining 31 samples were used to test the accuracy of the calibration. The NIRA calibrations were developed for two types of NIRA spectrophotometers, a scanner and a filter. Different mathematical treatments of the spectra were used before selecting the best set of wavelengths to predict AME_n; log 1/R, first derivative, and second derivative. Based on the standard error of the estimate (SEE), all calibrations showed good accuracy at predicting AME_n in poultry feeds. The best results were found using log 1/R for both the scanner (SEE = .058 kcal/g) and the filter instrument (SEE = .060 kcal/g). Principal component analysis, a multivariate statistical technique, was also employed in the predictions of AME_n and resulted in SEE of .080 kcal/g. The NIRA technique seems to have a potential as a fast, nondestructive method of AME_n analysis of poultry feed. (*Key words*: metabolizable energy, near infrared reflectance analysis, mathematical treatments, poultry, feeds)

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INTRODUCTION

The energy component of a diet is the most expensive and critical to animal performance. However, this major economic input is not controlled with any great precision, as most nutritionists rely on average book values for estimating the ME of ingredients and complete feeds. The reasons for the above are the time and cost involved in obtaining *in vivo* ME values through bioassays using either the classical approach or the so-called rapid bioassays (Sibbald, 1976; Farrell, 1978). Although indirect measurements of AME_n through prediction equations based on proximal components of the feeds have been developed (Carpenter and Clegg, 1956; Sibbald *et al.*, 1963), their success is limited to the use of specific dietary ingredients (Fisher, 1982). *In vitro* systems for predicting AME_n have also been developed (Furuya *et al.*, 1979; Clunnies *et al.*, 1984), but seem to have limited applications.

Near infrared reflectance analysis (NIRA), a technique that was first developed by K. F. Norris at the United States Department of Agriculture, Beltsville, Maryland (Norris, 1964) to measure moisture content, gained acceptance as an analytical tool because of its quickness, low operating cost, safety, and accuracy.

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TABLE 1. Ingredients used in the poultry diets for near infrared reflectance calibrations and validation sets

Corn	Canola meal	Limestone
Wheat	Corn gluten meal	Calcium
Barley	Fish meal (60% CP)	Phosphate
Oats	Feather meal	DL-methionine
Wheat bran	Meat meal	Choline chloride
Wheat middlings	Dry whey	Vitamin mix[1]
Wheat shorts	Blood meal	Mineral mix[1]
Milo	Cotton meal	
Rice hulls	Dehydrated alfalfa	
Animal and vegetable blend	Soybean alfalfa	
Corn oil		
Tallow		
Corn oil and tallow blend		

[1]These varied according to ration type.

Norris's (1964) work established the basis of modern NIRA technology in the food, feed, and grain industries. Since 1973, with the application of NIRA to the analysis of cereals and oil seeds (Williams, 1975), NIRA technology became widely accepted in food analysis, and instruments were developed to measure starch, oil, sugar, fiber, moisture, and protein; to be used especially in those areas where time is a critical factor. Its potential for rapidly evaluating forage quality was first demonstrated by Norris *et al.* (1976) followed by Shenk *et al.* (1979) and others (Ward *et al.*, 1982; Valdes *et al.*, 1985b, 1990; Abrams *et al.*, 1987). This technique also has been applied to predicting protein content in animal feed mixes (Williams and Starkey, 1980; Chen *et al.*, 1986; Valdes *et al.*, 1989).

In poultry nutrition studies, NIRA has been used for measuring chemical composition of poultry feeds (Valdes *et al.*, 1985a) and carcass composition in broiler and layers (Valdes and Summers, 1986; Valdes *et al.*, 1989). Moreover, measurements of digestible energy in feeds and forages have been reported using high-precision spectrophotometers (Bengtsson and Larsson, 1984; Redshaw *et al.*, 1986). Because all energy-yielding components of feeds absorb in the near infrared region of the spectrum, NIRA has the potential as a fast alternative method to measure AME_n in poultry feeds. The objective of the present study was to assess the usefulness of NIRA as a potential technique to measure AME_n in complete poultry feeds.

MATERIALS AND METHODS

Diets

Eighty poultry feeds that included rations for layers, broilers, and turkeys, and protein supplements with known AME_n were used in the current study. The AME_n values ranged from 2.120 to 3.553 kcal/g and were determined by bioassays conducted from November, 1987 to September, 1990. The diets represented a combination of 20 different ingredients plus mixtures of vitamins and minerals (Table 1). Diets were sampled at the moment of mixing and placed in glass bottles with screw lids. Two samples per diet were obtained, one sample used for the chemical analyses [gross energy (GE), nitrogen, and dry matter] and the second sample was employed for NIRA. The diets were stored at 5 C until analyzed.

Bioassays

A total collection procedure was used to obtain the AME_n values. The methodology of Leeson *et al.* (1974) was followed. The photoperiod was 16 h/day and room temperature was maintained at 20 C. Mature (6 mo to 1 yr old), male Rhode Island White birds were employed for the bioassays and individually housed in metal cages. A completely randomized design was employed. Thus, five roosters were randomly assigned to each experimental diet. A control diet was tested every time a bioassay was conducted. Therefore, five diets plus a control diet were run simulta-

neously and a total of 30 roosters was used at any one time. A total of 80 bioassays was performed, and each of these involved a 3-day adaptation period followed by a 4-day collection period. Excreta collections were made on aluminum foil placed on top of a receiving tray in each cage. Feed intake was measured daily. Feathers, scales, and spilled feed were removed from the excreta three times daily and spilled feed was weighed.

At the end of the collection period, the excreta were wrapped in foil and dried in a forced-draught oven at 60 C for 72 h. Feed intake and excreta output of dry matter were recorded. Fecal samples were ground using a Christie Norris Mill (MU180)[3] fitted with a 1-mm screen and stored at 5 C until analyzed. Duplicate analyses for GE by adiabatic bomb calorimeter, nitrogen percentage by Kjelfoss (Association of Official Analytical Chemists, 1980, Method 7.021) and analytical moisture by drying the samples at 135 C for 2 h were conducted. The same analyses were performed on the feed samples after grinding samples with a Tecator Cyclotec Sample Mill[4] fitted with a 1-mm screen.

Calculation of Nitrogen-Corrected Apparent Metabolizable Energy

For the calculations of AME_n, the method of Scott *et al.* (1982) was followed. The formula used was

$$AME_n = \frac{(FI \times GE\ feed) - (EO \times GE\ excreta \pm CF)}{FI}$$

where FI = feed intake (grams); GE was measured in kilocalories per gram; EO = excreta output (grams); and CF = correction factor, 8.22 kcal/g nitrogen retained or excreted.

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Near Infrared Reflectance Analysis Equipment

Two types of NIRA equipment were used in the current study; a scanning InfraAlyzer 500[5] and a filter instrument, the InfraAlyzer 400R.[5] The optics of both instruments are described in the instrument manuals. The scanner optical head contains the light source (tungsten), chopper wheel, filter wheel, and an integrating sphere containing two lead sulfide photodetectors. The monochromator part of the assembly houses the monochromator grating, a variable slit assembly, and a heater that provides temperature stability.

The 1,400-nm range (1,100 to 2,500 nm) is normally scanned in 4-nm steps but with the potential to provide 700 data points per sample if scanned at 2-nm steps. In contrast, the filter instrument is fitted with 19 narrow bandpass interference filters (1,445 to 2,348 nm range) limiting the collection capability to 19 data points per sample. Both instruments incorporate an integrating sphere for effective capturing of the light reflected from the sample. Light impinging upon a sample is diffusely reflected from it and eventually captured by one of the two detectors. The signal from the detectors is amplified using a logarithmic response amplifier and recorded as log 1/R, where R is the reflectance.

Near Infrared Reflectance Calibrations

Samples for the calibration set were selected on the basis of the range of AME_n values and the ingredient composition of the poultry diets. Thus, all ingredients were equally represented in the calibration and validation sets. The validation set represented samples pooled from the same population of samples as those for the calibration set but not used in developing the calibrations. Moisture content for the calibration samples ranged between 7.8 and 13.5% and for the validation set between 7.9 and 13.3%. For the purpose of developing the NIRA calibrations (e.g., selection of wavelengths) for AME_n for both instruments, the IDAS (InfraAlyzer data analysis software[5]) computer program was employed. Calculations for selection of wavelengths were performed on a IBM personal computer Model 60.

Reflectance measurements on the selected calibration samples were obtained at 4 nm steps over the range 1,100 to 2,500 nm for a total of 351 data points per sample. Duplicate readings were obtained for all samples in the calibration set.

Selection of Wavelengths

Two selection procedures were used. For the filter instrument, a combination search procedure selected the best combination of three, four, five, six, and seven wavelengths, considering every possible combination. However, the search capabilities of the program only allowed for searching among 101 wavelengths. Thus, preselected wavelengths (n = 101) were a prerequisite to applying the combination search procedure.

For the scanner instrument, a step-up search procedure was used to select the best single wavelength and then add additional wavelengths one at a time until seven wavelengths were chosen. Based on a combination of factors such as number of independent variables, wavelengths, chemical interpretation of the wavelengths selected, *F* ratio and R^2, the best fitting equation to predict AME_n using NIRA was selected. This procedure of wavelength selection for the scanner instrument was also followed after spectral data was transformed to produce first derivative (D^1OD) and second derivative (D^2OD) spectra. The D^1OD are calculated mathematically from the log 1/R spectra as differences between log 1/R measurements. In the current study, gaps of 10 nm between segments were used with no previous smoothing procedure. Other gaps between segments were tested as well without any success (5 to 20 nm). In the same way, the D^2OD was calculated as the difference of two adjacent D^1OD measurements using gaps of 20 nm between segments.

Principal Component Analysis

For the scanner instrument, principal component analysis (PCA) was also applied to the spectra. This technique is used to avoid having to test all possible combinations of wavelengths by identifying the important features of large data sets and to describe the variation in multidimensional data by means of a small number of uncorrelated variables called principal components (Cowe and McNicol, 1985). Due to memory limitations in the computer, the spectra from which the principal components were calculated contained 281 wavelengths (5-nm intervals between wavelengths), instead of the original 351 data points. The advantage of PCA as a statistical method is that it allows the creation of variables called components, which are linear combinations of the original variables, eliminating collinearity among the independent variables [mutually orthogonal, $\Sigma_1 (X_{1i}; X_{2i} = 0)$]. For the PCA, the IDAS software was employed.

Validation of the Near Infrared Reflectance Analysis

The validation set was used to assess the accuracy of the NIRA calibration equations. These samples, as indicated above, were drawn from the same population of samples as the calibration set but were not used in the development of the calibrations. Simple linear regression analyses relating kilocalories per gram of AME_n to the values predicted with NIRA for all calibrations were calculated using the general equation:

$$y_{ij} = b_0 + b_i x + e_{ij}$$

where y is the AME_n value in kilocalories per gram; x is the AME_n values in kilocalories per gram predicted by NIRA; b_0 is the intercept or bias (nonrandom error); b_1 is the regression coefficient; and e_{ij} is the random error. To assess the accuracy of the NIRA calibrations the standard error of the estimate (SEE), and the bias or average difference between AME_n and NIRA values were calculated. The SEE was calculated from the residual variance of the fitted linear models (SAS Institute, 1981) as follows:

$$SEE = \sqrt{\frac{(\text{NIRA value} - AME_n \text{ value})^2}{n - 1}}$$

where n = the number of samples in set.

RESULTS AND DISCUSSION

The AME_n value for the control diet used in the determination of AME_n values

TABLE 2. Statistics for near infrared reflectance calibrations for nitrogen-corrected apparent metabolizable energy in poultry feeds using different mathematical treatments and different number of wavelengths

Instrument	Mathematical treatment[1]	Wavelengths	R^2	SE of estimate	Wavelengths (nm) and coefficients[2]	*F* ratio
		(no.)		(kcal ME/g)		
Scanner	Log 1/R	1	.63	.267	1,452 (4)	29
		2	.90	.147	1,520 (27), 1,876 (–25)	98
		3	.96	.094	2,216 (–149), 1,124 (2), 2,188 (146)	188
		4	.98	.066	2,216 (–224), 1,720 (18), 2,192 (212), 1,500 (–9)	320
		5	.98	.059	1,496 (192), 1,720 (24), 2,192 (187), 1,500 (–205), 2,220 (–201)	312
		6	.99	.057	1,460 (289), 1,716 (30), 2,184 (129), 1,500 (–60), 1,456 (–248), 2,228 (–142)	312
		7	.99	.051	2,172 (257), 1,712 (30), 2,180 (90), 1,492 (407), 2,228 (–143), 2,168 (–218), 1,496 (427)	319
Scanner	D^1OD	1	.93	.132	2,200 (152)	270
		2	.97	.093	2,200 (297), 1,990 (20)	312
		3	.97	.092	2,200 (260), 1,904 (20), 2,324 (35)	225
		4	.97	.084	2,200 (341), 1,112 (–258), 2,484 (90), 1,444 (147)	201
		5	.98	.083	2,200 (325), 1,116 (–181), 2,484 (126), 1,444 (142), 2,100 (81)	170
		6	.98	.082	2,200 (399), 1,176 (–289), 1,160 (166), 1,444 (192), 2,100 (113), 1,524 (–169)	157
		7	.98	.089	2,200 (402), 1,176 (–358), 1,160 (369), 1,444 (189), 2,100 (102), 1,524 (–152), 1,136 (–171)	141
Scanner	D^2OD	1	.90	.145	2,396 (70)	204
		2	.93	.132	2,396 (80), 2,336 (53)	135
		3	.95	.110	2,392 (120), 2,336 (105), 1,952 (26)	137
		4	.97	.098	1,732 (56), 1,876 (–18), 2,336 (65), 2,236 (66)	143
		5	.97	.090	1,732 (49), 1,876 (–21), 2,336 (50), 2,236 (132), 2,284 (79)	128
		6	.97	.090	1,736 (67), 1,880 (–20), 2,336 (78), 2,236 (132), 2,284 (99), 2,068 (–32)	120
		7	.98	.087	1,736 (69), 1,880 (–107), 2,328 (65) 2,240 (52), 1,360 (80), 2,068 (–71), 1,940 (–73)	87
Filter	Log 1/R	1	.62	.267	1,445 (4)	29
		2	.94	.118	2,190 (150), 2,208 (–151)	170
		3	.97	.084	2,190 (80), 2,230 (–98), 2,310 (14)	259
		4	.98	.063	1,680 (8), 2,208 (122), 2,230 (–174), 2,270 (40)	336
		5	.99	.054	1,722 (61), 1,734 (–54), 2,190 (105), 2,230 (–131), 2,270 (15)	331
		6	.99	.058	1,722 (28), 1,818 (–18), 2,190 (110), 2,230 (–135), 2,310 (–20), 2,336 (32)	277

[1]R = reflectance; D^1OD = first derivative spectra; D^2OD = second derivative spectra.

[2]Values in parentheses represent coefficients.

TABLE 3. Chemical assignments[1] of near infrared absorption bands selected to measure nitrogen-corrected apparent metabolizable energy in complete poultry diets

Mathematical treatment[2]	Wavelength	Bond vibration[3]	Structure[3]
Log 1/R (Scanner)	1,500	O-H str, first overtone, N-H str, first overtone	NH
	1,720		
	2,192	C-H str, first overtone	H-C-H
	2,216	CH_2 asym str, C = str	HC = CH
		CH str; C = 0 str	-CHO
Log 1/R (Filter)	1,680	C-H str, first overtone	Aromatic
	2,208	C-H str, C = 0 str comb	-CHO
	2,230	. . .	
	2,270	O-H str, C-O str comb	Cellulose (starch)

[1]Wheeler (1959).

[2]R = reflectance.

[3]str = stretching vibrations; asym = asymmetric bending vibration; comb = combination bands; others are standard abbreviations (Williams and Norris, 1987).

was 2.676 ± .076 (SEE) kcal/g (n = 16). The wavelengths and coefficients selected by using the different mathematical treatments are given in Table 2. Up to seven wavelengths were included in the calculations. As indicated above, the selection of the best wavelengths was based on the number of wavelengths, chemical relation of wavelengths to known chemical components, and the *F* ratio. However, the final assessment was done after the equation was tested with an unknown set of samples to predict AME_n (validation set).

The AME_n was best predicted in poultry feeds using four wavelengths that were obtained with the log 1/R as the mathematical treatment. The wavelengths selected were 1,500, 1,720, 2,216, and 2,192 nm. The type of bond vibration represented by the wavelengths and their chemical structure are given in Table 3 and they represent energy yielding components of the diet. Information relating wavelengths to AME_n is limited or nonexistent.

The accuracy of predicting AME_n in poultry feeds using different mathematical treatments is given in Table 4. The lowest SEE was observed when spectra was treated as log 1/R for both the scanner and filter instruments. Although slightly higher SEE were observed for derivatives and PCA, these mathematical treatments of the spectra also showed good predictions of AME_n (e.g., SEE < 100 kcal/kg). There were two outliers, i.e., diets that were overestimated or underestimated by all the equations tested. These two diets represented samples with high levels of added fat (corn oil and tallow mix at a 6% level of inclusion in a basal diet) and were used to determine the AME_n value of the fat mixture.

All equations showed good predictions, but SEE was lower for log 1/R followed by D^1OD and D^2OD, respectively, in the scanner instrument. Although the SEE obtained using derivatives were acceptable for AME_n determinations, these mathematical treatments did not improve accuracy, as has been reported previously

TABLE 4. Accuracy for predicting nitrogen-corrected apparent metabolizable energy with near infrared reflectance[1] using different mathematical teratments

Mathematical treatment[2]	SE of estimate
	(kcal ME/g)
Log 1/R (Scanner)	.058
Log 1/R (Filter)	.060
D^1OD (Scanner)	.074
D^2OD (Scanner)	.098
PCA (Scanner)	.080

[1]In validation set.

[2]R = reflectance; D^1OD = first derivative spectra; D^2OD = second derivative spectra; PCA = principal component analysis.

TABLE 5. Prediction of metabolizable energy (kilocalories per gram) of complete poultry feeds by near infrared reflectance (NIRA)[1]

Diet number	AME_n[2] ± SD	NIRA[3] ± bias			
		Scanner/instrument		Filter/instrument	
1,004	2.602 ± .065	2.611	−.009	2.673	−.071
1,005	2.600 ± .042	2.568	.032	2.596	.004
1,006	2.998 ± .023	2.949	.049	3.013	−.015
1,007	2.960 ± .036	2.894	.066	2.921	.039
1,009	2.824 ± .005	2.801	.023	2.852	.028
1,012	2.712 ± .024	2.772	−.060	2.815	.103
1,013	2.859 ± .036	2.795	.064	2.865	−.006
1,016	2.923 ± .060	2.966	−.043	3.052	−.129
1,022	2.976 ± .023	2.946	.030	2.968	.008
1,025	2.967 ± .094	2.915	.052	2.885	.082
1,027	3.276 ± .026	3.159	.117	3.266	.010
1,031	3.195 ± .022	3.175	.020	3.201	.006
1,034	2.824 ± .024	2.839	−.015	2.912	−.088
1,038	2.976 ± .036	2.950	.026	3.055	−.079
1,039	2.912 ± .035	2.836	.076	2.920	−.008
1,040	3.075 ± .038	3.010	.065	3.058	.017
1,043	2.834 ± .053	2.807	.027	2.865	−.031
1,044	2.765 ± .048	2.806	.041	2.809	−.044
1,059	2.772 ± .030	2.840	−.068	2.911	−.139
1,053	3.255 ± .014	3.339	−.084	3.330	−.075
1,058	3.278 ± .050	3.284	−.006	3.294	−.016
1,062	3.150 ± .045	3.040	.110	3.172	−.022
1,063	3.223 ± .076	3.070	.153	3.262	−.039
1,065	3.079 ± .047	3.101	−.022	3.161	−.082
1,067	2.894 ± .095	2.881	.013	2.796	.098
1,033	3.021 ± .053	2.981	.040	2.979	.042
2,008	3.197 ± .048	3.162	.035	3.325	−.128
2,009	3.318 ± .021	3.184	.134	3.338	−.020
2,012	3.037 ± .028	2.944	.093	3.108	−.071
2,039	3.457 ± .039	3.364	.093	3.455	.002
4,400	2.908 ± .020	2.902	.004	3.043	.137
$\bar{x}$ ± SD	2.996 ± .211	2.964 ± .192		3.029 ± .211	
R^2	. . .	.92		.92	
SE of estimate	. . .	.058		.060	
b[4]	. . .	1.06 ± .05		.96 ± .05	

[1]Validation set.

[2]Determined by bioassay.

[3]Spectra as Log 1/R, where R = reflectance.

[4]b = bias.

for other applications of NIRA (Williams and Norris, 1987). Derivatives have been widely used in NIRA by numerous researchers as an alternative approach to the problem of overlapping peaks and baseline corrections (Williams and Norris, 1987). Furthermore, in the current study prediction of AME_n using the filter instrument and log 1/R showed the same accuracy relative to predictions obtained with the scanner instrument using the same mathematical treatment (Table 5). These results are important when considering instrument costs.

The results of applying PCA for predicting AME_n in poultry feeds showed a SEE of .080 kcal/g. The first three principal components explained 99.7% of the variability of the data. Based on the SEE values for the prediction of AME_n, the results indicated that PCA and multiple linear regression models (MLR) performed equally well, with a slight advantage for MLR. However, the present results showed that the index of random error, which represents a measure of the sensitivity of the calibration equation to the random (noise) component of the absorb-

ance data, was greater for the log 1/R (scanner and filter instruments) than for the PCA data (300 versus 27 for MLR and PCA, respectively). This observation agrees with results obtained by Mark (1986). Selection of the proper wavelengths is one of the most difficult tasks of MLR calibrations. However, in PCA (regression), selection of wavelengths is unnecessary because all wavelengths are used in the analysis, thereby simplifying the process of variable selection and eliminating colinearity among independent variables. Because of the above reasons, PCA seems to be an ideal mathematical approach for NIRA.

The results of the current study indicated that NIRA has potential for measuring AME_n in complete poultry diets. Its speed, simplicity of operation, and low running costs make NIRA an attractive alternative to minimize or eliminate the use of bioassays.

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REFERENCES

Abrams, S. M., J. S. Shenk, M. O. Westerhaus, and P. E. Barton, 1987. Determination of forage quality by near infrared reflectance spectroscopy: efficacy of broad-based calibration equations. J. Dairy Sci. 70:806–813.

Association of Official Analytical Chemists, 1980. Official Methods of Analysis. 13th ed. Association of Official Analytical Chemists, Washington, DC.

Bengtsson, S., and K. Larsson, 1984. Prediction of the nutritive value of forages by near infrared reflectance photometry. J. Sci. Food Agric. 35: 951–958.

Carpenter, R. J., and R. M. Clegg, 1956. The metabolizable energy of poultry feeding stuffs in relation to their chemical composition. J. Sci. Food Agric. 7:45–51.

Chen, Shih-Ling Y., Ali Hsu, and Mane-Lane Lee, 1986. Application of near infrared reflectance spectroscopy to compositional analysis of commercial pig feed mixes. J. Assoc. Off. Anal. Chem. 70:420–423.

Clunnies, M., S. Leeson, and J. D. Summers, 1984. In vitro estimation of apparent metabolizable energy. Poultry Sci. 63:1033–1039.

Cowe, I. A., and J. W. McNicol, 1985. The use of principal components in the analysis of near infrared spectra. Appl. Spectrosc. 39:257–266.

Farrell, D. J., 1978. Rapid determination of metabolizable energy of foods using cockerels. Br. Poult. Sci. 19:303–308.

Fisher, C., 1982. Energy evaluation of poultry rations. Pages 113–140 *in*: Recent Advances in Animal Nutrition. W. Haresign, ed. Butterworths, London, England.

Furuya, S., K. Sakamoto, and S. Takahashi, 1979. A new in vitro method for the estimation of digestibility using the intestinal fluid of the pig. Br. J. Nutr. 41:511–520.

Leeson, S., K. N. Boorman, and D. Lewis, 1974. Metabolizable energy studies with turkeys: metabolizable energy of dietary ingredients. Br. Poult. Sci. 15:183–189.

Mark, H., 1986. Comparative study of calibration methods for near infrared reflectance analysis using a nested experimental design. Anal. Chem. 58:2814–2819.

Norris, K. H., R. F. Barnes, D. E. Moore, and J. S. Shenk, 1976. Predicting forage quality by infrared reflectance spectrometry. J. Anim. Sci. 43: 889–897.

Norris, K. H., 1964. Simple spectroradiometer for 0.4 to 1.2 micron region. Trans. Am. Soc. Agric. Eng. 7:240–242.

Redshaw, E. S., G. W. Mathison, L. P. Milligan, and R. D. Weisenburger, 1986. Near infrared reflectance spectroscopy for predicting forage composition and voluntary consumption and digestibility in cattle and sheep. Can. J. Anim. Sci. 66: 103–115.

SAS Institute, 1981. SAS® for Linear Models. A. Allen Ray, ed. SAS Institute Inc., Raleigh, NC.

Scott, M. L., M. C. Nesheim, and R. J. Young, 1982. Nutrition of the Chicken. M. L. Scott and Associates, Ithaca, NY.

Shenk, J. S., M. O. Westerhaus, and M. R. Hoover, 1979. Analysis of forages by infrared reflectance. J. Dairy Sci. 62:807–812.

Sibbald, I. R., 1976. A bioassay for true metabolizable energy in feedingstuffs. Poultry Sci. 55:303–308.

Sibbald, I. R., J. Czarnocki, S. J. Slinger, and G. C. Ashton, 1963. The prediction of the metabolizable energy content of poultry feedstuffs from a knowledge of their chemical components. Poultry Sci. 42:386–392.

Valdes, E. V., J. A. Atkinson, J. W. Hilton, and S. Leeson, 1989. Near infrared reflectance analysis of fat, protein and gross energy of chicken and rainbow trout carcasses. Can. J. Anim. Sci. 69: 1087–1090.

Valdes, E. V., G. E. Jones, and G. J. Hoekstra, 1990. Effect of growing year and application of a multi-year calibration for predicting quality parameters by near infrared reflectance spectroscopy in whole-plant corn forage. Can. J. Plant Sci. 70:747–755.

Valdes, E. V., and J. D. Summers, 1986. Determination of crude protein and fat in carcass and breast muscle samples of poultry by near

infrared reflectance spectroscopy (NIR). Poultry Sci. 65:485–490.

Valdes, E. V., L. G. Young, S. Leeson, I. McMillan, and F. Portela, 1985a. Chemical analysis of poultry feeds by near infrared reflectance spectroscopy. Poultry Sci. 64:2136–2142.

Valdes, E. V., L. G. Young, I. McMillan, and J. E. Winch, 1985b. Analysis of hay, haylage and corn silage samples by near infrared reflectance spectroscopy. Can. J. Anim. Sci. 65:753–760.

Ward, R. G., G. S. Smith, J. D. Wallace, N. S. Urquhart, and J. S. Shenk, 1982. Estimates of intakes and quality of grazed range forage by near infrared reflectance spectroscopy. J. Anim. Sci. 54:399–402.

Wheeler, O. H., 1959. Near infrared spectra of organic compounds. Chem. Rev. 59:629–666.

Williams, P. C., 1975. Application of near infrared reflectance spectroscopy to analysis of cereal grains and oilseeds. Cereal Chem. 52:561–576.

Williams, P. C., and K. H. Norris, 1987. Near Infrared Reflectance Technology in the Agricultural and Food Industries. P. C. Williams and K. H. Norris, ed. American Association Cereal Chemistry, St. Paul, MN.

Williams, P. C., and P. M. Starkey, 1980. Influence of feed ingredients upon the prediction of protein in animal feed-mixes by near infrared reflectance spectroscopy. J. Sci. Food Agric. 31: 1201–1213.