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Variation and Correlation of Shearing Force with Feed Nutritional Characteristics of Wheat Straw

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ABSTRACT: This experiment was conducted to study the variation laws and correlations of shearing force and feed characteristics including morphological characteristic, chemical composition and *in situ* degradability of wheat straw. Feasibility of evaluating the nutritional value of wheat straws with shearing force values was analyzed in this study. Six hundred wheat straw plants (*Jimai 22*) were randomly selected and placed in a cool and ventilated place. Samples were collected in the 1st, 15th, 30th, 45th, 60th d after harvest to measure shearing force, morphological characteristic, nutritional composition. Rumen degradation of dry matter (DM), neutral detergent fiber (NDF) and acid detergent fiber (ADF) of wheat straws were determined by the nylon bags method. The results demonstrated that linear and quadratic effects of storage time on all the tested morphological characteristics were significantly correlative ($p<0.01$). As storage time goes on, all the tested nutrients and their rumen degradations of wheat straw was linearly ($p<0.01$) and quadratic ($p<0.01$) correlative except ADF content and rumen degradation of ADF. Significant correlations were determined in linear effect of shearing force on morphological characteristics ($p<0.01$), and linear density and diameter were a more sensitive predictor than stem thickness for shearing force. There were strong correlations between storage time and all the measured physical characteristics (shearing force, morphological characteristics and shearing force standardized by morphological characteristics) ($p<0.01$). Nutrition compositions were linearly correlative with shearing force and standardized shearing force ($p<0.01$). The linear correlation between rumen degradation of DM and NDF and shearing force and standardized shearing force were evident ($p<0.01$). In conclusion, shearing force, nutrition compositions and their rumen degradation of wheat straw were still dynamic with storage time after harvest. Correlation could be found between shearing force and nutritional characteristics of wheat straw. Nutrient content, morphological index and rumen degradation of DM and NDF could be predicted by changes in shearing force. Shearing force should be applied according to a standardized storage time when it is used to forecast the feed value of wheat straws. (**Key Words:** Wheat Straw, Shearing Force, Morphological Characteristic, Nutrient Compositions, *In situ* Degradability, Correlativity)

INTRODUCTION

Forage intake and its degradability in ruminants are great determinative factors of animal performance (Iwaasa et al., 1996). Straw is the major roughage source in agricultural areas in China. Mature crop straws are used directly or processed to feed ruminant. Therefore, research into finding a fast assessment method of determining crop straw nutritional value would be an important foundation for the comprehensive utilization of crop straw resources.

It is important to find a physical measurement which can explain the differences in forage breakdown during mastication that better determines the variation in dry matter consumption than does the nutrient composition of the forage. Shearing force describes the force required to fracture a plant when applied at 90 degrees to the plant surface and has been used to physically characterize forages (Mackinnon et al., 1988; Inoue et al., 1994). Herrero et al. (2001) found that both the grinding resistance and the shear strength technique were able to detect differences between four species of *Brachiaria* and ages of re-growth.

There were many reports that sheep fed with low shearing force ryegrass leaves have higher dry matter consumption (Mackinnon et al., 1988; Inoue et al., 1994b). Many studies about correlations between shearing force and feed characteristics of grass were found. For example, shearing force of alfalfa stems (Iwaasa et al., 1996, 1998; Liu et al., 2009), shearing force of perennial ryegrass (Evans, 1967a,b; Inoue et al., 1994a,b) and shearing force

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of maize plants (Chen et al., 2007). Shearing force was also related to chemical constituents. Correlations were found between shearing force and crude fiber concentration (Wilson, 1965; Evans, 1967b; Akira Kokubo et al., 1989; Akira Kokubo et al., 1991). Recently, results from our laboratory reported that shearing force is an important indicator of forage nutritive value (Liu et al., 2009).

Although shearing force can be used as a good indicator of nutritive value of forage, there is no information about temporal variation in the shearing force of wheat straw. We do not know the correlation of different storage times of wheat straw with changes in shearing force and feed nutritional characteristics. Thus, this study had two objectives: i) to study relationships between shearing force and standardized shearing force (of diameter, thickness and linear density), nutrient composition and *in situ* degradability of wheat straw, ii) to investigate the changing laws and the relationships of temporal variation on shearing force and nutrient composition of wheat straw, and confirm that shearing force is one way of evaluating nutrient composition of forage.

MATERIALS AND METHODS

Shearing force and morphological measurements of wheat straw

Six hundred wheat straw plants (*Jimai 22*) harvested at wax ripeness stage were obtained from an experimental field in the Livestock Research Center at Shandong Agricultural University. The whole plant was cut about 5.0 cm above ground and all male and female ears were removed from the straw. Wheat straws plants were randomly allocated into 5 groups (120 wheat straw plants per treatment) that were then randomly assigned to 4 batches (30 units per batch). The samples were placed in a cool (20°C) and ventilated place with ventilation equipment and collected in the 1st, 15th, 30th, 45th, 60th d after harvest to measure shearing force, morphological characteristics and nutrition composition.

Each wheat straw was weighed and length measured. Linear density was the weight per millimeter of wheat straw length. All samples were cut at two horizons, being one-third and two-thirds of the straw length sheared at the middle of each segment and the results were averaged to give the shear force value over these three horizons. Diameters were measured at the approximate midpoint of each segment and an average was calculated as the straw diameter. Straw thickness was measured when the hollow straw was compacted at the approximate midpoint of each segment and an average was calculated as the straw thickness. Linear density, diameter and straw thickness were used for the purpose of standardizing shear strength parameters for wheat straw morphology, as there were large differences among individuals with different storage time. It's worth noting that each segment was sheared at the approximate midpoint ensuring that the location was between two nodes to prevent any influence of nodes on shearing force.

Shearing force was measured with a Portable Shear Force Apparatus made by Shandong Agricultural University and specially used to measure toughness of plant tissues (Liu et al., 2009). Range of shearing force was 0 to 200 kg.

Chemical analysis

Wheat straw that had been measured for morphological characteristics was ground according to Feng (2004). Six hundred wheat straw plants were randomly allocated into 5 treatments with 4 replicates according to the storage time, and 30 wheat straws were merged into one sample. Straw was cut into segments shorter than 5 mm and then milled by WK-400B high speed beater (Shanghai xinnuo equipment co., LTD) for 30 s. One part of the ground sample was used to determine *in situ* degradability and the other part was used for chemical analysis. Moisture content was determined by oven-drying at 65°C to a constant weight, dry matter (DM) content was determined by forced-air oven at 105°C to a constant weight, and organic matter (OM) was incinerated at 450°C. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed according to Goering and Van Soest et al. (1970), and *in situ* degradability according to Tilley and Terry (1963). Hemicellulose (ADS) concentration was calculated as the difference between NDF and ADF concentrations. The CP was determined by a Kjeldahl procedure using a Kjeltec Auto 1030 Analyzer (Tecator, Hoganas, Sweden).

In situ degradability

Three Xiao Wei sheep, fitted with a permanent rumen fistula, aged 4 yrs and of 35.8 kg live weight (S.D. 4.54), were used to determine *in situ* degradability (of DM, NDF and ADF) of wheat straw. Sheep were housed in a room in which temperature was maintained constant at 20°C and had free access to drinking water. Sheep were fed with a diet of 40% sweet potato vines, 30% wheat straw and 30% corn-based concentrate supplement (Table 1). Daily ration was 1.6 kg DM, given in two equal portions (07:00 and 16:00). Sheep were adapted to their diet for 10 d before the *in situ* degradability trial formally started.

In situ degradability was determined during the collection phase using Dacron bags (Shanghai Quancheng Environmental Protection Technology Co.). Dimensions of the bags were 17 cm×9 cm with a pore size of 37 μm (Mehrez, 1977). An average of 4 g of sample, which had been milled by high speed beater for 30 s, was weighed into the Dacron bags. All bags containing samples were soaked in distilled water at 38°C for 10 min. A pair of bags was

Table 1. The composition of concentrate (air-dry basis)

Ingredients	Percentage (%)
Corn	75.00
Wheat bran	10.00
Soybean meal	12.00
NaCl	1.00
Dicalcium phosphate	0.50
Limestone	0.50
Premix[1]	1.00
Total	100.00

[1] Supplied per kg of Premix: Vitamin A 1,500,000 IU, Vitamin D_3 250,000 IU, Vitamin E 5,000 mg, Fe 17,000 mg, Zn 15,000 mg, Mn 6,000 mg, Cu 1,600 mg, Co 110 mg, Se 200 mg.

also incubated in deionized water at 38°C for 10 min to estimate washout at time zero for each sample. Three Dacron bags with different samples were tied to a plastic leader, which was attached to a nylon line, and incubated in the rumen. Samples were removed from each sheep and analyzed after 48 h. Nylon bags removed from the rumen were thoroughly washed under running tap water, and then dried to a constant weight in a forced-air oven at 105°C. DM losses were determined by differences between the initial dry matter incubated and the dry matter that remained after incubation corrected for the zero time weight. NDF and ADF losses were determined in a similar method.

Statistical analysis

An average was calculated for the shearing force of 30 straws in one group; similarly for wheat straw diameter and linear density. Values obtained from individual replicate samples were used as units for statistical analysis. The significance of differences among treatments was tested by Duncan's multiple-range test. A level of $p<0.05$ was used as the criterion for statistical significance. Pearson correlation coefficients (R) between shearing force and linear density, diameter, thickness, nutrient composition and *in situ* degradability were determined using the PORC CORR procedure (SAS, Institute, Inc., 1999). Linear regression analysis was done to determine the correlation of shearing force with morphological characteristics, nutrient composition, *in situ* degradability and storage time of wheat straw.

RESULTS

Physical characters

Morphological characteristics and shearing force: Linear density, shearing force, shearing force/linear density, shearing force/diameter and shearing force/straw thickness were linearly ($p<0.01$) and/or quadratic ($p<0.01$) decreased, yet diameter and straw thickness were linearly ($p<0.01$) and/or quadratic ($p<0.01$) increased during the trial period.

Correlations between shearing force and morphological characteristic: The significant correlation between shearing force and morphological characteristics of wheat straw is shown in Table 3. As one important morphological characteristic of forage, linear density was positively related to shearing force as shown in Table 3, p value was lower than 0.01, while r was 0.953. Diameter and straw thickness had high negative correlation ($p<0.01$), while r was -0.921 and -0.916, respectively. With the slope of the linear equation, linear density and diameter having a higher absolute value than straw thickness, linear density and

Table 2. Morphological characteristics and shear power at different storage times

Morphological characteristics	Storage time					SEM[1]	Effects (p values)[2]	
	1 d	15 d	30 d	45 d	60 d		L	Q
Linear density (mg/mm)	2.^{61a}	2.48^{b}	2.47^{b}	2.45^{b}	2.37^{c}	0.006	<0.001	<0.001
Diameter (mm)	4.70^{b}	4.79^{b}	4.93^{a}	4.94^{a}	5.04^{a}	0.015	<0.001	<0.001
Straw thickness (mm)	0.90^{c}	0.99^{b}	0.96^{b}	0.99^{b}	1.08^{a}	0.007	<0.001	<0.001
Shearing force (kg)	6.84^{a}	5.71^{b}	5.64^{b}	5.19^{c}	4.63^{d}	0.057	<0.001	<0.001
Shearing force/linear density (kg/mg mm)	2.62^{a}	2.30^{b}	2.28^{b}	2.12^{c}	1.96^{d}	0.021	<0.001	<0.001
Shearing force/diameter (kg/mm)	1.46^{a}	1.19^{b}	1.14^{c}	1.05^{c}	0.92^{d}	0.015	<0.001	<0.001
Shearing force/straw thickness (kg/mm)	7.65^{a}	5.77^{b}	5.87^{b}	5.23^{b}	4.28^{c}	0.100	<0.001	<0.001

[1] SEM = Standard error of mean. [2] p values for the linear (L) or quadratic (Q) effects of storage time on morphological characteristics.

[a-d] Means within a row with different superscript letters differ ($p<0.05$).

Table 3. Linear relationships between morphological characteristics (y) and shearing force (x) (sample size, n = 20)

Morphological characteristics	Linear equation	r[1]	p	SD[2]	Slope±SE[3]
Linear density (mg/mm)	$y = 0.10103x+1.9095$	0.953	<0.001	0.026	0.101±0.008
Diameter (mm)	$y = -0.1063x+5.7806$	-0.921	<0.001	0.055	-0.160±0.016
Straw thickness (mm)	$y = -0.07933+1.42996$	-0.916	<0.001	0.028	-0.079±0.008

[1] r for Pearson correlation coefficients between shearing force and linear density, diameter and straw thickness.

[2] SD = Sample standard deviation. [3] Slope±SE = The slope of the equation±standard error.

Table 4. Linear relationships between physical characteristics (y) and days (x, 1 to 60 d) (sample size, n = 20)

Morphological characteristics	Linear equation	r[1]	p	SD[2]	Slope±SE[3]
Shearing force (kg)	y = -0.03331x+6.60842	-0.913	<0.001	0.328	-0.033±0.004
Shearing force/ Linear density (kg/mg mm)	y = 0.42074x-0.2452	0.999	<0.001	0.299	0.421±0.003
Shearing force/ Diameter (kg/mm)	y = 0.19841x+0.09554	1.000	<0.001	0.126	-0.198±0.001
Shearing force/ Straw thickness (kg/mm)	y = 0.93633x+1.35587	0.996	<0.001	1.907	-0.936±0.020
Linear density (mg/mm)	y = -0.00343x+2.5791	-0.888	<0.001	0.039	-0.003±4.196E-4
Diameter (mm)	y = 0.00558x+4.71391	0.879	<0.001	0.067	0.006±7.134E-4
Straw thickness (mm)	y = 0.00258x+0.90762	0.816	<0.001	0.040	0.003±4.304E-4

[1] r for Pearson correlation coefficients between shearing force and linear density, diameter and straw thickness.

[2] SD = Sample standard deviation. [3] Slope±SE = The slope of the equation±standard error.

diameter were the preferable sensitive predictors for shearing force rather than straw thickness.

The relationships between physical characteristics and days (1 d to 60 d) are shown in Table 4. There were positive relationships between all the measured physical characteristics and days ($p<0.01$), except shearing force and linear density with days which had a negative correlation ($r = -0.888$, $r = -0.913$, respectively). Shearing force and linear density were linearly ($p<0.01$) decreased with advancing storage time, yet the other physical characteristics were linearly ($p<0.01$) increased. When shearing force was standardized for stem linear density, stem diameter or straw thickness, the correlations still existed, even more strongly ($p<0.01$). As shown in Table 3, there were extremely significant correlations between shearing force and days when shearing force was standardized for morphological characteristics such as linear density, diameter or straw thickness, and r was 0.999, 1.000 and 0.996, respectively. Shearing force/linear density and shearing force/diameter had a higher slope absolute value than other morphological characteristics.

Nutrient composition

Nutrient levels of different storage time: Nutrient levels of test material are shown in Table 5. All the tested ingredients of wheat straw increased ($p<0.01$) as storage time increased (1 to 60 d), except moisture content which decreased ($p<0.01$). However, linear or quadratic effects of storage time on the content and *in situ* degradability of ADF were not observed ($p>0.01$).

Correlations between shear power and nutrient composition of straw: Linear relationships between shearing force and standardized shearing force (shearing force/linear density, shearing force/diameter, shearing force/straw thickness) and chemical compositions are shown in Table 6. The linear relationships between moisture and DM content had higher absolute values of Pearson correlation coefficients with the four measurements of physical strength ($p<0.01$), than with the other chemical compositions, and ADF concentration had the lowest correlations with the four measurements of physical strength ($p<0.01$). There were positive relationships among shearing force and standardized shearing force with moisture and OM content ($p<0.01$), while others were negatively correlated ($p<0.01$). Results demonstrated that all of the relationships between shear power and nutrient composition were prominent ($p<0.01$), especially for moisture content which had the greatest slope value, and

Table 5. Nutrient levels of wheat straw

Indexes %	Storage time					SEM[1]	Effects (p values)[2]	
	1 d	15 d	30 d	45 d	60 d		L	Q
Air-dry basis								
DM	93.89^{c}	96.68^{b}	96.80^{ab}	97.29^{a}	97.24^{ab}	0.083	<0.001	<0.001
Fresh basis								
Moisture	14.84^{a}	9.18^{b}	9.20^{b}	8.28^{b}	7.94^{b}	0.231	<0.001	<0.001
NDF	71.23^{b}	74.18^{a}	74.52^{a}	73.81^{a}	74.31^{a}	0.134	0.003	<0.001
ADF	47.09^{d}	48.65^{ab}	48.71^{a}	48.03^{c}	48.28^{bc}	0.059	0.086	<0.001
ADS	24.42^{b}	25.79^{a}	25.90^{a}	25.91^{a}	25.98^{a}	0.093	0.002	<0.001
CP	4.50^{c}	5.59^{b}	5.88^{a}	5.85^{ab}	5.77^{ab}	0.038	<0.001	<0.001
OM	90.98^{a}	92.65^{bc}	90.76^{b}	90.58^{cd}	90.49^{d}	0.019	<0.001	<0.001
DM degradability	43.22^{c}	44.97^{b}	45.28^{b}	46.76^{a}	46.99^{a}	0.180	<0.001	<0.001
NDF degradability	29.92^{c}	31.15^{b}	31.21^{b}	32.07^{a}	32.44^{a}	0.127	<0.001	<0.001
ADF degradability	28.94	29.34	29.50	29.42	29.48	0.169	0.315	0.486

[1] SEM = Standard error of mean. [2] p values for the linear (L) or quadratic (Q) effects of storage time on morphological characteristics.

$^{a\text{-}d}$ Means within a row with different superscript letters differ ($p<0.05$).

Table 6. Linear relationships between nutrient composition (y) and shear power (x) (sample size, n = 20)

Measurements (%)	Index	Linear equation	r[1]	p	SD[2]	Slope±SE[3]
Shearing force (kg)	Moisture	$y = 3.22002x-8.15166$	0.918	<0.001	1.123	3.220±0.329
	DM	$y = -1.57678x+105.21243$	-0.919	<0.001	0.545	-1.577±0.160
	OM	$y = 0.21743x+89.47123$	0.899	<0.001	0.085	0.217±0.025
	CP	$y = -0.60619x+8.91367$	-0.860	<0.001	0.290	-0.606±0.085
	NDF	$y = -1.41417x+81.53188$	-0.818	<0.001	0.801	-1.414±0.235
	ADF	$y = -0.5166x+51.04478$	-0.628	<0.001	0.516	-0.516±0.151
	ADS	$y = -0.73344x+29.71009$	-0.806	<0.001	0.434	-0.733±0.127
Shearing force/linear density (kg/mg mm)	Moisture	$y = 10.2951x-13.33209$	0.905	<0.001	1.203	10.295±1.143
	DM	$y = -5.01151x+107.68196$	-0.900	<0.001	0.601	-5.012±0.570
	OM	$y = 0.70235x+89.10534$	0.896	<0.001	0.086	0.702±0.082
	CP	$y = -1.91649x+9.84015$	-0.838	<0.001	0.309	-1.916±0.294
	NDF	$y = -4.4591x+83.6665$	-0.795	<0.001	0.844	-4.460±0.802
	ADF	$y = -1.58418x+51.72362$	-0.594	0.006	0.533	-1.584±0.506
	ADS	$y = -2.34039x+30.87975$	-0.793	<0.001	0.447	-2.340±0.424
Shearing force/diameter (kg/mm)	Moisture	$y = 13.01709x-5.1202$	0.919	<0.001	1.113	13.017±1.316
	DM	$y = -6.38525x+103.74069$	-0.922	<0.001	0.535	-6.385±0.633
	OM	$y = 0.86782x+89.6889$	0.890	<0.001	0.089	0.868±0.105
	CP	$y = -2.48505x+8.38276$	-0.873	<0.001	0.276	-2.485±0.327
	NDF	$y = -5.79657x+80.29244$	-0.830	<0.001	0.776	-5.797±0.917
	ADF	$y = -2.13414x+50.61116$	-0.642	0.002	0.508	-2.134±0.600
	ADS	$y = -3.0204x+29.08352$	-0.822	<0.001	0.417	-3.020±0.493
Shearing force/straw thickness (kg/mm)	Moisture	$y = 2.10715x-2.24976$	0.921	<0.001	1.103	2.107±0.211
	DM	$y = -1.01752x+102.23993$	-0.909	<0.001	0.576	-1.018±0.110
	OM	$y = 0.14614x+89.84769$	0.927	<0.001	0.073	0.146±0.014
	CP	$y = -0.3876x+7.75028$	-0.843	<0.001	0.305	-0.388±0.058
	NDF	$y = -0.92629x+78.94488$	-0.821	<0.001	0.795	-0.926±0.152
	ADF	$y = -0.34618x+50.14467$	-0.645	0.002	0.506	-0.346±0.097
	ADS	$y = -0.49861x+28.47323$	-0.840	<0.001	0.398	-0.499±0.076

[1] r for Pearson correlation coefficients between shearing force and linear density, diameter and straw thickness.

[2] SD = Sample standard deviation. [3] Slope±SE = The slope value of the equation±standard error.

these along with the four measurements of physical strength could best be predicted by shear power.

Relationships between shear power and in situ degradability of straw: *In situ* degradability (of DM, NDF or ADF) were related to shearing force and standardized shearing force such as shearing force per unit of linear density, stem diameter or straw thickness (Table 7). As shown in Table 7, a negative correlation existed between shearing force (or standardized shearing force) and *in situ* degradability (of DM and NDF). Interestingly, NDF degradability had the highest r value, but DM degradability had highest slope absolute value.

Linear relationships between days (1 to 60 d) and *in situ* degradability (of DM, NDF and ADF) are shown in Table 8. Positive correlations existed between days (1 to 60 d) and DM degradability (r = 0.858) and NDF degradability (r = 0.839), especially for the DM degradability, which had the highest slope value. DM degradability and NDF degradability linearly increased over a 60-d period, the straw would be digested easier and better at the 60th d.

DISCUSSION

Our laboratory's related research demonstrated that the variance in stem shearing force is due to a combination of factors, including changes in chemical composition and morphological characteristics. Generally, shearing force is easy to measure and it can be used as an indicator of forage nutritive value (Liu et al., 2009).

Shearing force is significantly correlated with diameter, weight, linear density and the cell wall chemical constituents of the stem (Mowat et al., 1967; Iwaasa et al., 1996, 1998). Linear density (weight per unit of straw length) has been used in attempts to relate morphological characteristic to shearing force. Stem density may be influenced by a combination of anatomical features and cell wall chemical constituents. Esau (1977) found that lignin and hemicelluloses are important constituents of the

Table 7. Linear relationships between shear power (x) and *in situ* degradability of nutrient composition (y) (sample size, n = 20)

Measurements (%)	Degradability	Linear equation	r[1]	p	SD[2]	Slope±SE[3]
Shearing force (kg)	DM	y = -1.87007x+55.91658	-0.931	<0.001	0.592	-1.870±0.173
	NDF	y = -1.22599x+38.22409	-0.934	<0.001	0.377	-1.226±0.110
	ADF	y = -0.3449x+31.2683	-0.384	0.095	0.667	-0.345±0.195
Shearing force/linear density (kg/mg mm)	DM	y = -6.14991x+59.31062	-0.944	<0.001	0.535	-6.150±0.508
	NDF	y = -4.00877x+40.39729	-0.942	<0.001	0.354	-4.009±0.336
	ADF	y = -1.24273x+32.13898	-0.427	0.061	0.624	-1.243±0.621
Shearing force/diameter (kg/mm)	DM	y = -7.57828x+54.17726	-0.934	<0.001	0.576	-7.578±0.681
	NDF	y = -5.0013x+37.122	-0.944	<0.001	0.347	-5.001±0.411
	ADF	y = -1.48118x+31.0438	-0.409	0.074	0.660	-1.481±0.780
Shearing force/straw thickness (kg/mm)	DM	y = -1.19796x+52.34037	-0.914	<0.001	0.656	-1.198±0.125
	NDF	y = -0.80431x+35.9887	-0.940	<0.001	0.361	-0.804±0.069
	ADF	y = -0.25855x+30.82536	-0.441	0.051	0.649	-0.259±0.124

[1] r for Pearson correlation coefficients between shearing force and linear density, diameter and straw thickness.

[2] SD = sample standard deviation. [3] Slope±SE = the slope of the equation±Standard error.

cellulose framework of the cell wall, providing rigidity to the wall and influencing stem density. Linear relationships between shearing strength and linear density in forage species, such as ryegrass and timothy, have been found many of researchers (McClellad and Spielrein, 1957; Iwaasa et al., 1996; Liu et al., 2009). Some results showed that diameter was more sensitive than linear density and stem thickness in affecting shearing force, also linear density was more important than chemical composition in affecting shearing force (Liu et al., 2009). In our study, shearing force of wheat straw decreased with decreasing linear density. A similar relationship was observed by Herrero et al. (2001). Linear density changes were more sensitive in causing changes in shearing force than diameter and straw thickness. Meanwhile, all the tested morphological characteristics were linearly and/or quadratic changed during the trial period. Also we found that either the linear relationships between morphological characteristics and shearing force or the linear relationships between physical characteristics and days (1 to 60 d) were strong. Physical characteristics were related to shearing force by varying degree depending upon storage time.

Moisture content of the stem was also an important factor affected shearing force. Prince et al. (1965) found that mechanical properties of alfalfa stems were sensitive to moisture content, which supports the results of our study. Shearing force increased with decreasing moisture content, which was due to fiber tensile strength being related to moisture content (Chen et al., 2007; Liu et al., 2009). The direct relationship between moisture content and dry matter content described by these authors can lead to a change in shearing force as was found in our study and supports our conclusion. Other nutrient composition also can have a connection with shearing force, for example, crude protein; those pastures containing high amounts of fibrous components had lower CP and degradability values. These relationships are widely documented. In the special work of Hughes et al. (2000), CP was shown to have negative correlations with NDF, ADF and lignin. Obviously, we found negative relation between CP and shear power was legitimately. Straws were interrupted by water supply and were in the limits of coercion after harvest, physiological activities of stalks can be caused a series of changes in the various nutrients content. Many factors may lead to its nutrient content relative increase over the 60-d period, water loss faster than the loss of nutrients (e.g., CP), and thus, most of measured values in our study were increased relatively.

Shearing force measured in this study is a net result of the combination of all compounds in the plant material, not an individual one. Previous studies (Mackinnon et al., 1988; Kokubo et al., 1989; Hughes et al., 2000) have shown that stem linear density, stem diameter and chemical constituents of stem could also influence shearing force. A study by Wilson (1965) found that leaf tensile strength could predict cellulose content in *Lolium perenne*.

Table 8. Linear relationships between days (x, 1 to 60 d) and *in situ* degradability of nutrient composition (y) (sample size, n = 20)

Degradability	Linear equation	r[1]	p	SD[2]	Slope±SE[3]
DM	y = 0.06288x+43.54045	0.858	<0.001	0.831	0.063±0.009
NDF	y = 0.04013x+30.14343	0.839	<0.001	0.575	0.040±0.006
ADF	y = 0.00769x+29.10363	0.235	0.319	0.702	0.008±0.008

[1] r for Pearson correlation coefficients between shearing force and linear density, diameter and straw thickness. [2] SD = Sample standard deviation.

[3] Slope±SE = The slope of the equation±standard error.

Increasing levels of the cell wall chemical constituents such as cellulose and lignin have been reported to cause a shearing force increase (Evans, 1967a; b). In our study, all of NDF, ADF and ADS were important determinants of shearing force, which are cell wall chemical constituents, were correlated with shearing force. This was consistent with the study by Iwaasa et al. (1996), and supported the conclusion of Evans (1967a; b). As the important components of secondary cell wall thickening, cellulose and hemicelluloses should be associated with the physical strength characteristics, and significant correlations were found in our study between hemicelluloses and shearing force. The results are consistent with early reports that shearing force is influenced by cell wall chemical constituents (Kokubo et al., 1989; 1991). Akira Kokubo et al. (1989) indicated that lower cellulose content of the brittle culm of barley (*Hordeum vulgare* L.) was strongly correlated with brittleness. Furthermore, Akira Kokubo et al. (1991) pointed out that brittleness of mutant culms is due to fewer numbers of cellulose molecules in the cell walls of barley (*Hordeum vulgare* L.). Obviously, the filling and binding action of hemicelluloses and lignin to the cellulose matrix rather than increasing levels of cellulose concentration, increased stem density and shearing force. Iwaasa et al. (1996) reported that the effect of cellulose on shearing force was influenced by the orientation of its fibrils or other chemical components like silica or lignin. In a word, it was not necessarily the amount of cellulose, lignin or hemicelluloses but their interaction that affects cell wall composition, linear density and shearing force.

The *in situ* degradability (of DM, NDF and ADF) was the nutritive value index of forage, the relationship between straw shearing force and rumen degradability was strong. It is important to determine whether *in situ* degradability showed a relationship with a simple physical measure, like shearing force. However, there was not much information about the relationship between wheat straw shearing force and its *in situ* degradability. In our study, shearing force influenced *in situ* degradability (of DM, NDF and ADF), the degradability of both DM and NDF were negatively related to shear power. This result was consistent with the report of Herrro et al. (2001) that there was a negative correlation between shear strength and *in vitro* degradability. These relationships could be explained by the differences in chemical concentration which were related to shearing force.

Considerable variation in rumen degradability of roughage is closely associated with variation in cell wall concentration and components. In the particular work reviewed by Wilkins (1966), lignin was more closely related to *in situ* degradability of OM and DM and the potential degradability of cellulose which was contained in NDF had significant negative correlations with both lignin content and lignified tissue (Wilkins, 1972). Liu et al. (2009) found there was a positive relationship between shearing force and lignin content, and increasing shearing force indicated more lignin was contained in cell wall and resulted in a lower *in situ* degradability (of DM and NDF) of alfalfa. Hemicellulose, as another cell wall chemical constituent, was also closely related to shear power in our study, which supported our conclusion and complemented our laboratory's previous studies.

Shear power had a negative relationship with straw degradability (of DM and NDF), meanwhile, a positive correlation was found between storage time and *in situ* degradability (of DM and NDF). In the work reviewed by Wilson (1994) and Wilson et al. (1989), different anatomical tissue components have different relative weights, cellular densities and rates of fermentation within the rumen. However, there are few studies of the effect of physical characteristics on the relationship between shearing force and straw degradability. In our study, when shearing force was standardized for linear density, diameter and stem thickness, the relationship between shearing force and degradability was consistent. These linear relationships were also found between *in situ* degradability of nutritional matter and storage time (1 to 60 d), shearing force and standardized shearing force in our study, which supports our conclusion. Certainly, research in this field should be investigated further and in more detail.

IMPLICATIONS

It can be concluded from our research that the shearing force, nutrient compositions and *in situ* degradability of wheat straw were still dynamic after harvest (1 to 60 d stage). There were correlations between shearing force and feed characteristics of wheat straw. Nutrient content, morphological index and rumen degradability of nutrients (dry matter and neutral detergent fiber) can be predicted by changes in shearing force. Shearing force was a more direct indicator than chemical constituents because it can be measured easily and used as a good indicator of forage nutritive value. Shearing force values should be applied according to storage time when it is used to forecast the feed value of wheat straws. Future research should explore the relationships between shearing force and silication and lignification of cell wall and effects of silication of cell wall on shearing force and nutritive value of plants.

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