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Assessment of nutritive value of cereal and legume straws based on chemical composition and *in vitro* digestibility

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Abstract: The nutritive value of 17 straws was determined on the basis of their chemical composition, *in vitro* dry matter (DM) digestibility and rumen fermentation kinetics (from gas production curves measured *in vitro*). Five roughages were from the cereal species *Avena sativa* (oat), *Hordeum vulgare* (barley), *Secale cereale* (rye), *Triticum aestivum* (wheat) and *Zea mays* (maize stover). The other 12 samples were legume straws, two samples from each of the species *Cicer arietinum* (chickpea), *Lens culinaris* (lentil) and *Phaseolus vulgaris* (bean) and one sample from each of the species *Lathyrus sativus* (chickling vetch), *Lupinus albus* (white lupin), *Pisum sativum* (field pea), *Vicia articulata* (one-flowered vetch), *Vicia ervilia* (bitter vetch) and *Vicia sativa* (common vetch). All samples were collected after harvesting from different farms located in León (northwestern Spain). Based on their chemical composition, digestibility and gas production characteristics, species could be clustered into two groups with a significant linkage distance, one for cereal straws that merged at a level of similarity of 80% and the other for legume straws with a degree of similarity of 50%. Species varied widely and significant differences ($P < 0.05$) were observed between the two groups of straws. Legume straws showed higher crude protein (74 ± 6.1 vs 29 ± 2.2 g kg^{-1} DM) and lower fibre (584 ± 18.1 vs 793 ± 27.5 g neutral detergent fibre kg^{-1} DM) contents than cereal straws and, consequently, DM digestibility coefficients (0.670 vs 0.609; standard error of difference 0.0054) and metabolisable energy values (7.4 ± 0.15 vs 5.7 ± 0.24 MJ kg^{-1} DM) were significantly greater in legume than in cereal straws. Although there were noticeable differences among species within each botanical family, legume straws showed better nutritional quality than cereal straws, indicating that they could be considered promising and interesting sources of roughage for incorporation into ruminant diets.

Keywords: cereal straw; legume straw; nutritive value; gas production; *in vitro* digestibility; extent of degradation

INTRODUCTION

Cereals and some legumes are cultivated to obtain grain for human consumption or for animal feed.[1,2] Crop residues after harvesting can represent a substantial amount of biomass, considered an agricultural waste for which there are few alternative uses. Straw is one of the main by-products from cereal and grain legume crops and, given the importance of such crops, is produced in large quantities all over the world.[3] In the European Union (EU) there is a large surplus of cereal straws, as these resources are scarcely used. There is also some yield of straw from the cultivation of legumes to obtain grain for animal feed or pulses for humans, especially in the Mediterranean basin. This production is expected to expand, as the EU is encouraging these crops within the framework of more sustainable agriculture and with a move away from imported soy from the USA.[1,2] The disposal of such material may represent an unaffordable cost for farmers, but the accumulation of huge amounts

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of underutilised waste could spoil and pollute the countryside and thus is not environmentally desirable. Recently, farmers have been encouraged to seek uses for straw instead of burning it. Usually, some of this residue is used as organic manure incorporated into the soil after harvesting, but straws have also been used in animal husbandry as bedding or as feed. By using straw as animal feed rather than disposing of it by landfilling or incineration, both economic and environmental costs associated with these latter practices are eliminated.

The use of cereal straw as animal feed is limited owing to its low nutritive value, as it is a fibrous material of low digestibility, energy value and protein content.[4] Straw alone is not sufficient to maintain the animal, but it may represent a suitable source of roughage if properly supplemented, making up a considerable proportion of diets for animals with low nutrient requirements. Under severe shortage of hay, straw can become a valuable low-cost forage that can be used effectively, especially in extensive ruminant production systems based on low inputs. Despite their abundance, straws have generally been overlooked as animal feed, in many cases owing to insufficient knowledge about their potential feeding value. To provide balanced diets that include straw, it is important to know the nutritive value of this roughage and its variability, as different straw sources vary in their nutrient content and digestibility. Cereal straws have been studied extensively,[5–8] but much less information is available about legume straws obtained after harvesting pulse crops or legume grains for animal feed.

Chemical composition, in combination with *in vitro* digestibility, is a useful indicator for preliminary evaluation of the likely nutritive value of feedstuffs. This study was designed to determine the chemical composition and *in vitro* digestibility of several cereal and legume straws.

EXPERIMENTAL

Seventeen samples of cereal (five samples) and legume (twelve samples) straws were collected from uplands of the province of León (northwestern Spain). The sampling area is at an altitude of 900 m above sea level, with mean annual rainfall and temperature of 564 mm and 10.6 °C respectively. Cereal straws were from the species *Avena sativa* L (oat), *Hordeum vulgare* L (barley), *Secale cereale* L (rye), *Triticum aestivum* L (wheat) and *Zea mays* L (maize stover). The nine legume species from which straw was collected after harvesting the pulses or beans were *Cicer arietinum* L (chickpea), *Lathyrus sativus* L (chickling vetch), *Lens culinaris* Medik (lentil), *Lupinus albus* L (white lupin), *Phaseolus vulgaris* L (bean), *Pisum sativum* L (field pea), *Vicia articulata* Hornem (one-flowered vetch), *Vicia ervilia* (L) Willd (bitter vetch) and *Vicia sativa* L (common vetch). Two samples of each of the three legume species *C arietinum*, *L culinaris* and *P vulgaris* were collected. In one of these samples (whole straw, W sample), leaves and pods were retained to represent a similar proportion as in the plant before harvesting. The other sample (S sample) contained a higher proportion of stems (stalks) as in the straw obtained when crops are harvested using a combine harvester, where a substantial loss of leaves and pods occurs. All samples were collected from barns or fields after crops had been combined and/or threshed under practical agricultural conditions. The crops were harvested when the plants were dry and grains or pulses had a low moisture content. Therefore all straws can be regarded as mostly dried at harvest, with a dry matter (DM) content over 85%. The cereal and stem-rich legume straws were obtained after straight combine harvesting of the crops. In this mechanical process, straw is discharged in windrows after the plant is cut and the grain collected. The other legume straws were obtained after a traditional harvest of the crops, which consists of pulling up the plant by hand, then threshing on the floor to separate the seeds from the stalks.

In the laboratory, all samples were oven dried at 60 °C, then ground to pass through a 1 mm screen. Straw samples were analysed for organic matter (OM), ether extract (EE) and crude protein (CP) following the methods of the AOAC.[9] Neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) were determined according to Van Soest *et al*,[10] following the modifications proposed by ANKOM.[11] Hemicellulose was estimated by difference as NDF − ADF, whereas cellulose was calculated as ADF − lignin. Neutral detergent-soluble carbohydrates (NDSC) were estimated by difference as OM − EE − CP − NDF.

Rumen fluid for the *in vitro* assays was obtained from four Merino sheep housed in individual cages, fitted with rumen fistula and fed 1 kg of alfalfa hay daily and with free access to water and mineral/vitamin licks. A sample of rumen contents was collected before the morning meal in thermos flasks and taken immediately to the laboratory, where it was strained through layers of cheesecloth and kept at 39 °C under a CO_2 atmosphere.

Gas production was determined as described by Theodorou *et al*.[12] Ground samples (500 mg) were mixed with 50 ml of diluted rumen fluid and incubated at 39 °C in gas-tight culture bottles under a CO_2 atmosphere. The rumen fluid was previously diluted (1:4 v/v) with a culture medium containing macro- and micro-mineral solutions, resazurin and a bicarbonate buffer solution and prepared as described by Menke and Steingass.[13] The medium was kept at 39 °C and saturated with CO_2. Oxygen in the medium was reduced by the addition of a solution containing cysteine hydrochloride and Na_2S. Four bottles were incubated as blanks and used to compensate for gas production in the absence of substrate. All the bottles were then crimped, shaken and placed in the incubator. The volume of gas produced was recorded at different incubation times (3, 6, 9, 12, 16, 20,

24, 30, 36, 48, 60, 72, 96, 120 and 144 h after inoculation time) using a pressure transducer.[12] At the end of the incubation period (144 h) the contents of each serum bottle were filtered using sintered glass crucibles under vacuum. A sample of the filtrate was collected to measure pH and determine total volatile fatty acid (VFA) concentration and molar proportions by gas–liquid chromatography with flame ionisation detection, using ethylbutyric acid as the internal standard, whereas the incubation residue was oven dried at 100 °C for 48 h to estimate the potential DM disappearance (D144). Two incubation trials were conducted, using two bottles per straw in each of them, giving a total of four observations per sample over the two experiments. The volume of gas produced after 24 h of incubation was used with CP and EE contents to estimate metabolisable energy (ME) concentration in MJ kg^{-1} DM, using the equations proposed by Menke and Steingass.[13] To estimate the kinetics of gas production, data on cumulative gas volume produced were fitted using the generalised Mitscherlich model proposed by France *et al*:[14]

$$G = A(1 - e^{-c(t-L)-d(\sqrt{t}-\sqrt{L})})$$

where G (ml) denotes cumulative gas production at time t, A (ml) is asymptotic gas production, c (h^{-1}) and d ($h^{-1/2}$) are rate constants and L (h) is lag time. The half-life ($t_{1/2}$, h) of the degradable fraction of each substrate was calculated as the time taken for gas accumulation to reach 50% of its asymptotic value. The fractional degradation rate at $t_{1/2}$ ($\mu_{1/2}$, h^{-1}) was calculated as

$$\mu_{1/2} = c + \frac{d}{2\sqrt{t_{1/2}}}.$$

The extent of degradation in the rumen (E) for a given rate of passage (k, h^{-1}) was estimated by numerical integration from mathematical expressions derived by France *et al*.[15] To calculate E, a mean retention time of digesta in the rumen of 30 h was assumed, giving a rate of passage of 0.033 h^{-1} (characteristic of sheep fed a forage diet at maintenance level).

The technique proposed by Van Soest *et al*[16] was used to assess *in vitro* DM digestibility. Modifications proposed by ANKOM[11] were introduced. Rumen fluid was diluted in the medium (prepared as described above) in the proportion 1:4 (v/v). Samples (250 mg) were weighed out into artificial fibre bags (size 5 cm × 5 cm, pore size 20 μm), which were heat sealed and placed in 5 l incubation jars (up to 24 bags per jar). Each incubation jar was filled with 2 l of buffered rumen fluid transferred anaerobically, and the contents were thoroughly mixed. The jars were closed with a plastic lid provided with a single-way valve that prevents the accumulation of fermentation gases, and placed in a revolving incubator (ANKOM Daisy incubator, ANKOM Technology Corp, Macedon, NY, USA) at 39 °C, with continuous rotation to facilitate effective immersion of the bags in rumen fluid. After 48 h of incubation in buffered rumen fluid, samples were rinsed gently in cold water, oven dried and weighed. In a second stage, bags were subjected to neutral detergent extraction at 100 °C for 1 h. According to Van Soest *et al*,[16] extraction with neutral detergent removes bacterial cell walls and other endogenous products and therefore predicts true *in vitro* DM digestibility (DMD). Considering the amount of NDF incubated, *in vitro* cell wall digestibility (CWD) could be estimated. Four observations per sample were obtained in two incubation runs, with duplicate determinations in each one.

Analysis of variance[17] was carried out on *in vitro* digestibility and gas production kinetic parameters, with straw as the only source of variation (one-way ANOVA). Orthogonal contrasts were used for the comparison between cereal and legume straws. Multivariate cluster analysis was performed using the data on chemical composition, *in vitro* digestibility and gas production kinetics to study emerging groupings of the straws. The method used for hierarchical agglomerative linkage was complete linkage clustering based on a furthest-neighbour criterion, with the furthest pair of observations between two groups used to determine (dis)similarity of the two groups.[18] The similarity and dissimilarity measures were calculated as squared Euclidean distances. The SAS package was used for ANOVA and cluster analyses.

RESULTS

Data on chemical composition of the straws are shown in Table 1. Chemical composition was highly variable, not only between straw types but also within each class of straw. All species studied had similar OM content and none had a particularly high ash content. However, their CP content varied widely, ranging from 25 to 36 g kg^{-1} DM in cereal straws and from 43 to 111 g kg^{-1} DM in legume straws. Cereal straws had higher NDF (793 ± 27.5 vs 584 ± 18.1 g kg^{-1} DM) and lower NDSC (115 ± 27.3 vs 244 ± 12.3 g kg^{-1} DM) contents than legume straws. Composition of the cell wall fraction (represented by NDF) also differed between the two types of straw, with higher ADF/NDF (0.71 ± 0.012 vs 0.60 ± 0.020) and lignin/NDF (0.15 ± 0.008 vs 0.07 ± 0.007) ratios for legume than for cereal straws. The proportion of hemicellulose in the cell wall averaged 0.40 ± 0.020 and 0.29 ± 0.012 for cereal and legume straws respectively, whereas mean values of cellulose as a proportion of NDF were 0.53 ± 0.019 and 0.56 ± 0.016 for cereal and legume straws respectively. ME concentration was significantly lower in cereal (mean value 5.7 ± 0.24, ranging from 5.1 to 6.3 MJ ME kg^{-1} DM) than in legume (mean value 7.4 ± 0.15, ranging from 6.5 to 8.3 MJ ME kg^{-1} DM) straws.

Gas production kinetic parameters of the straws are presented in Table 2. Although the kinetics of gas production was variable across the straws

Table 1. Chemical composition (g kg^{-1} dry matter) and metabolisable energy concentration (MJ kg^{-1} dry matter) of cereal and legume straws

Plant species	Organic matter	Crude protein	Ether extract	NDF	ADF	Lignin	NDSC	Metabolisable energy
Cereal straws								
Avena sativa	950	26	7	795	505	58	122	5.1
Hordeum vulgare	938	33	8	716	423	68	181	6.0
Secale cereale	962	25	8	844	544	55	85	5.1
Triticum aestivum	946	27	12	750	445	53	158	5.8
Zea mays	933	36	9	862	458	46	27	6.3
Legume straws								
Cicer arietinum (W)	924	72	16	639	468	101	196	7.2
Cicer arietinum (S)	920	43	10	669	477	115	199	6.5
Lathyrus sativus	907	92	24	539	384	82	252	7.6
Lens culinaris (W)	888	111	22	454	280	80	301	8.3
Lens culinaris (S)	940	58	10	663	500	115	210	6.7
Lupinus albus	943	56	8	588	420	61	290	7.7
Phaseolus vulgaris (W)	908	67	7	511	373	54	323	8.0
Phaseolus vulgaris (S)	919	69	8	611	465	86	231	7.3
Pisum sativum	897	65	21	548	384	60	262	7.7
Vicia articulata	929	103	7	586	421	91	233	7.1
Vicia ervilia	932	96	6	600	436	95	230	7.2
Vicia sativa	877	60	15	600	390	104	201	7.3

NDF = neutral detergent fibre; ADF = acid detergent fibre; NDSC = neutral detergent-soluble carbohydrates; W = leaf-rich straw; S = stem-rich straw.

Table 2. Mean values of parameters estimated by fitting generalised Mitscherlich model to gas production profiles recorded for different cereal and legume straws

Plant species	*A* (ml gas g^{-1} DM)	*c* (h^{-1})	*d* (h$^{-1/2}$)	Lag time (h)	Half-life (h)	Fermentation rate (h^{-1})
Cereal straws						
Avena sativa	283	0.031	−0.073	1.15	35.5	0.025
Hordeum vulgare	304	0.021	0.015	0.49	29.8	0.023
Secale cereale	303	0.049	−0.219	4.99	36.1	0.031
Triticum aestivum	284	0.030	−0.034	0.00	29.2	0.027
Zea mays	316	0.050	−0.097	7.50	26.7	0.040
Legume straws						
Cicer arietinum (W)	254	0.033	0.078	1.52	15.9	0.043
Cicer arietinum (S)	235	0.035	0.059	1.24	16.1	0.043
Lathyrus sativus	238	0.041	0.101	1.52	13.2	0.055
Lens culinaris (W)	287	0.030	0.139	2.11	14.6	0.049
Lens culinaris (S)	228	0.049	0.021	1.26	15.0	0.052
Lupinus albus	271	0.063	−0.038	0.49	14.0	0.058
Phaseolus vulgaris (W)	278	0.065	−0.022	0.67	13.3	0.062
Phaseolus vulgaris (S)	248	0.066	−0.065	0.71	14.6	0.057
Pisum sativum	271	0.050	−0.006	0.84	15.5	0.050
Vicia articulata	237	0.056	−0.038	0.52	15.7	0.051
Vicia ervilia	235	0.047	0.055	1.78	13.8	0.054
Vicia sativa	262	0.031	0.097	1.15	14.9	0.044
SED	12.8	0.0115	0.0690	0.705	1.36	0.0044
Cereal (C)	298	0.036	−0.082	2.83	31.5	0.029
Legume (L)	254	0.046	0.040	1.22	14.7	0.052
SED for contrast C vs L	4.9	0.0044	0.0266	0.272	0.52	0.0017

A is asymptotic gas production; *c* and *d* are rate constants; DM = dry matter; W = leaf-rich straw; S = stem-rich straw; SED = standard error of difference.

examined, some trends in the comparison between cereal and legume straws are noteworthy. Asymptotic gas production was significantly higher in cereal than in legume straws. However, values of the rate constants (*c* and *d*) were lower and lag times longer for cereal than for legume straws, resulting in faster fermentation rates and shorter half-lives for legume compared with cereal straws.

In vitro digestibility coefficients determined by different approaches are given in Table 3. Despite interspecies variation within each type of straw, there were significant ($P < 0.05$) differences between cereal and legume straws. Thus cell wall digestibility and potential DM disappearance (after 144 h of incubation) were greater for cereal straws, whereas legumes showed significantly higher coefficients of DM digestibility and

Table 3. Coefficients (g digested g^{-1} incubated) of *in vitro* dry matter and neutral detergent fibre digestibility (DMD and NDFD respectively), dry matter disappearance after 144 h of incubation *in vitro* (D144) and estimated extent of dry matter degradation in rumen (*E*) for different cereal and legume straws

Plant species	DMD	NDFD	D144	*E*
Cereal straws				
Avena sativa	0.542	0.424	0.647	0.225
Hordeum vulgare	0.600	0.493	0.662	0.273
Secale cereale	0.586	0.509	0.673	0.221
Triticum aestivum	0.602	0.469	0.620	0.252
Zea mays	0.712	0.666	0.725	0.293
Legume straws				
Cicer arietinum (W)	0.610	0.398	0.598	0.334
Cicer arietinum (S)	0.543	0.330	0.547	0.305
Lathyrus sativus	0.682	0.411	0.613	0.366
Lens culinaris (W)	0.770	0.493	0.709	0.405
Lens culinaris (S)	0.573	0.357	0.536	0.307
Lupinus albus	0.693	0.478	0.667	0.398
Phaseolus vulgaris (W)	0.744	0.500	0.670	0.406
Phaseolus vulgaris (S)	0.680	0.476	0.625	0.367
Pisum sativum	0.704	0.455	0.625	0.357
Vicia articulata	0.659	0.418	0.613	0.347
Vicia ervilia	0.658	0.431	0.610	0.362
Vicia sativa	0.670	0.450	0.627	0.357
SED	0.0140	0.0250	0.0207	0.0139
Cereal (C)	0.609	0.512	0.665	0.253
Legume (L)	0.670	0.432	0.620	0.359
SED for contrast C vs L	0.0054	0.0097	0.0080	0.0054

W = leaf-rich straw; S = stem-rich straw; SED = standard error of difference.

Table 4. Fermentation pattern parameters determined after *in vitro* incubation (144 h) of cereal and legume straws in diluted rumen fluid

Parameter	Cereal straws	Legume straws
Partitioning factor (mg DM digested ml^{-1} gas)	2.23 (0.027)	2.45 (0.040)
Total VFA (mmol g^{-1} DM incubated)	6.38 (0.194)	5.47 (0.167)
VFA (mmol g^{-1} DM digested)	9.58 (0.100)	9.12 (0.286)
Acetate (mmol mol^{-1} VFA)	606 (4.5)	614 (6.5)
Propionate (mmol mol^{-1} VFA)	258 (5.7)	220 (4.1)
Butyrate (mmol mol^{-1} VFA)	103 (3.1)	113 (3.7)
Iso-acids (mmol mol^{-1} VFA)	24.3 (1.49)	33.8 (4.14)
Acetate/propionate ratio	2.35 (0.071)	2.80 (0.075)

DM = dry matter; VFA = volatile fatty acids. Standard error of each mean is shown in parentheses.

ruminal degradability estimated from the gas production profiles.

Fermentation parameters observed when cereal and legume straws were incubated in buffered rumen fluid are presented in Table 4. Fermentation of cereal straws resulted in greater gas volume and VFA production mg^{-1} DM digested and in a lower acetate/propionate ratio and iso-acid (isobutyrate and isovalerate) molar proportion than when legume straws were fermented.

DISCUSSION

Chemical composition and energy concentration of the cereal straws were within the range of values reported by other authors.[5–8,19] Much less information has been published on legume straws, but our values are comparable to those reported in the literature,[20–25] intermediate between those for a medium-quality hay and those for the cereal straws.

Figure 1 shows a dendrogram representing a hierarchy of categories, based on degree of similarity resulting from the cluster analysis, which gives a description of the relationships between the different straws. The plot clearly discriminates cereal and legume straws, which were clustered into two groups with a significant level of dissimilarity (largest linkage distance), confirming that straws included within each group share a significant number of characteristics in terms of chemical composition and *in vitro* digestibility. Although the differences between legume and cereal straws accounted for a high proportion of the variance among samples, there was some variability within each of the main groups of straws. Within the legume straws, up to two clusters were detected. In one of them, four straws were clustered with a level of similarity over 95%, namely those with the highest DM digestibility coefficients. The other group merged at a level of similarity of 85% and comprised the other eight straws. This intra-class variation cannot be attributed only to likely differences among

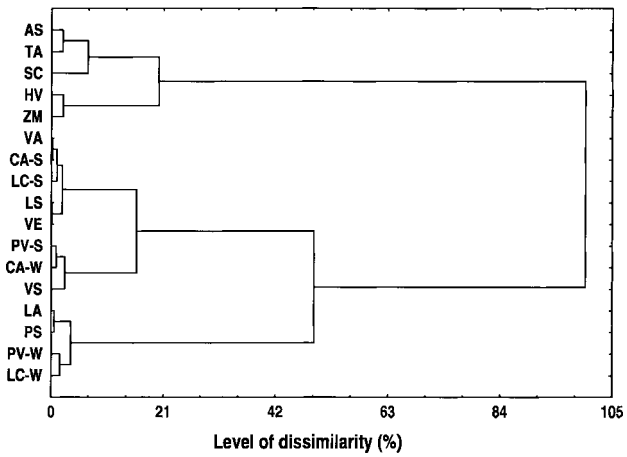

Figure 1. Horizontal hierarchical tree plot showing clustering of different straws based on similarities in chemical composition and *in vitro* digestibility: AS = *Avena sativa*; TA = *Triticum aestivum*; SC = *Secale cereale*; HV = *Hordeum vulgare*; ZM = *Zea mays*; VA = *Vicia articulata*; CA = *Cicer arietinum*; LC = *Lens culinaris*; LS = *Lathyrus sativus*; VE = *Vicia ervilia*; PV = *Phaseolus vulgaris*; VS = *Vicia sativa*; LA = *Lupinus albus*; PS = *Pisum sativum*; W = leaf-rich straw; S = stem-rich straw.

species.[19,26] Other factors are known to affect the composition and digestibility of straws, such as variety or cultivar,[8,27] environmental and seasonal effects,[28,29] proportion of different morphological fractions (stems, leaves, blades, sheaths, chaff, pods)[30–32] and stage of maturity at harvest.[20] The leaf/stem ratio as affected by harvesting conditions may determine to a great extent the nutritive value of straw, especially for legume species, owing to brittleness of the leaves causing greater loss of this fraction. The differences observed herein between leaf-rich (W sample) and stem-rich (S sample) legume straws confirms the importance of morphological composition of the straw to its nutritive value, so that leaf loss should be prevented if the straw is going to be used as an animal feed.

In general, legume straws showed higher CP and ME concentrations and lower NDF contents than cereal straws.[23,27] Owing to their greater proportion of highly digestible cell contents, DM digestibility and rumen degradability of the legume straws were on average higher (10 and 42% respectively) than those of the cereal straws.[25] However, cell wall digestibility and potential degradability (as DM disappearance after 144 h of incubation *in vitro*) were higher (15 and 7% respectively) in cereal than in legume straws, probably owing to their lower cell wall lignification and their higher hemicellulose content, which is the most digestible cell wall component. Cell wall composition also accounts for significant differences between cereal and legume straws in their degradation kinetics in the rumen. Cereal straws showed higher asymptotic gas production, confirming once more that they are potentially more degradable, but also a longer lag time and a slower degradation rate, with large differences in both half-life and fractional fermentation rate (Table 2). These results suggest that the maximum extent of degradation (asymptote) is reached after different incubation times depending on the type of straw incubated (earlier with legume than with cereal straws). Legumes and grasses are degraded by rumen micro-organisms by different mechanisms of colonisation and digestion.[14,33] Legumes have a higher content of pectins than grasses, and these carbohydrates are important components of the intercellular spaces and are degraded promptly and extensively by rumen micro-organisms. In contrast, hemicelluloses and cellulose are degraded at significantly slower rates.[33,34] Overall dry matter digestion of forages is highly dependent on structural factors such as the relative proportion of cell types present in the plant tissues and the existence of factors restricting microbial access to walls.[34] There are significant differences between plant tissues in their rumen degradability, and these differences are not consistent across plant parts, particularly across families (ie grasses and legumes).[35] In relation to the presence of antinutritional factors, although moderate concentrations of tannins have been detected in forage legumes, Makkar *et al*[23] found negligible levels of tannins and phenols in legume straws.

Therefore cereal straws are potentially more digestible than legume straws provided that residence time in the rumen is long enough to enable extensive degradation of their less lignified cell walls. However, as the degradation rate of cereal straws is very slow, it is expected that these straws are degraded in the rumen to a lesser extent than legume straws even at slow passage rates, as for instance in animals fed at maintenance level. Higher CP content and degradation rate of legume compared with cereal straws could also result in a greater voluntary intake of leguminous roughages.[25,36]

Analysis of differences between cereal and legume straws in some of the parameters that define their fermentation patterns in the rumen (Table 4) is also of interest. There were significant differences between the two types of straw in total VFA production and in the molar proportions of each acid. Total VFA production (per unit of substrate fermented) and the proportion of propionate were increased when cereal straws were incubated, despite their higher NDF content compared with legume straws. However, the neutral detergent-soluble carbohydrates include some fibre carbohydrates such as pectins, β-glucans and fructans whose fermentation in the rumen gives a higher acetate/propionate ratio than starch and sugars.[37] Pectins are found in substantial quantities in legume forages and would be included in the NDSC fraction, which would explain in part the VFA molar proportion observed when legume straws were incubated *in vitro*.

The ratio of substrate truly degraded (mg) to volume of gas produced (ml) has been termed the partitioning factor (PF) and may reflect variations in microbial biomass yield.[38] The value of PF varies for different chemical entities (eg fibre, non-structural carbohydrates, protein) of the feedstuffs, and it is assumed that the higher the value of PF, the more efficient the fermentation is. The average PF value measured after 144 h of incubation was greater for legume than for cereal straws, indicating a higher fermentation efficiency for legume straws and that a greater portion of the degraded substrate is converted to microbial biomass or VFA.[27] It is noteworthy that rumen degradation of cereal straws resulted in higher VFA production (expressed as g^{-1} substrate incubated or fermented). Thus it is possible that microbial biomass synthesis is favoured when legume straws are degraded compared with cereal straws, which could be attributed to their higher CP content. The production of branched chain VFA is related to the degradation of some amino acids, and thus the higher molar proportion of iso-acids could be attributed to a higher release of rumen-degradable nitrogen when legume straws are degraded and fermented in the rumen. When the N content is very low as in the cereal straws, microbial growth may be limited by a shortage in N supply.[39] The availability of fermentable energy

can also be a constraint for microbial growth in the rumen.[19] The faster degradation rate of legume straws could also be associated with enhanced microbial growth when N supply is not so constrained.

The availability of nutrients from straws is much lower than the energy potentially stored in these feedstuffs. Thus a number of physical, chemical and biological (enzymatic or microbiological) treatments have been proposed to upgrade the nutritive value of straws[3,4] by increasing their digestibility through structural modifications of the polysaccharide–lignin crosslinks of the cell wall. Some treatments (ammoniation) also increase the N content of the straw.[4] These treatments have been applied widely to cereal straws, but little is known about their applicability to legume straws, although it has been suggested that the treatments improve the nutritive value of poorer-quality straws to a greater extent than that of better-quality roughages.[6]

CONCLUSIONS

Legume straws are generally of better nutritional quality than cereal straws owing to their higher nitrogen and lower fibre contents. Despite their greater lignification, legume straws are degraded in the rumen at a faster rate than cereal straws, leading to a higher extent of degradation and, consequently, to higher dry matter digestibility. The large variability among cereal and legume species within each group is noteworthy, as are the differences between samples of the same species.

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REFERENCES

1 López L, Grain legumes for animal feed, in *Neglected Crops: 1492 from a Different Perspective*, Vol 26 of *Plant Production and Protection Series*, ed by Hernando Bermejo JE and León J. FAO, Rome, pp 273–288 (1994).

2 Cubero JI, Traditional varieties of grain legumes for human consumption, in *Neglected Crops: 1492 from a Different Perspective*, Vol 26 of *Plant Production and Protection Series*, ed by Hernando Bermejo JE and León J. FAO, Rome, pp 289–301 (1994).

3 Flachowsky G, Kamra DN and Zadrazil F, Cereal straws as animal feed—possibilities and limitations. *J Appl Anim Res* **16**:105–118 (1999).

4 Fondevila M, Muñoz F, Joy M and Castrillo C, Utilización de la paja de cereales: tratamientos y suplementación. *Ovis* **11**:73–86 (1990).

5 Theander O and Åman P, Anatomical and chemical characteristics, in *Straws and Other Fibrous By-products as Feed*, ed by Sundstøl F and Owen E. Elsevier, Amsterdam, pp 45–78 (1984).

6 Tuah AK, Lufadeju E, Ørskov ER and Blackett GA, Rumen degradation of straw. 1. Untreated and ammonia-treated barley, oat and wheat straw varieties and triticale straw. *Anim Prod* **43**:261–269 (1986).

7 Givens DI, Everington JM and Adamson AH, Chemical-composition, digestibility *in vitro*, and digestibility and energy value *in vivo* of untreated cereal straws produced on farms throughout England. *Anim Feed Sci Technol* **26**:323–335 (1989).

8 Ørskov ER, Shand WJ, Tedesco D and Morrice LAF, Rumen degradation of straw. 10. Consistency of differences in nutritive-value between varieties of cereal straws. *Anim Prod* **51**:155–162 (1990).

9 AOAC, *Official Methods of Analysis*, 16th edn. AOAC International, Arlington, VA (1995).

10 Van Soest PJ, Robertson JB and Lewis BA, Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J Dairy Sci* **74**:3583–3597 (1991).

11 Ammar H, Lopez S, Bochi O, García R and Ranilla MJ, Composition and *in vitro* digestibility of leaves and stems of grasses and legumes harvested from permanent mountain meadows at different maturity stages. *J Anim Feed Sci* **8**:599–610 (1999).

12 Theodorou MK, Williams BA, Dhanoa MS, McAllan AB and France J, A simple gas production method using a pressure transducer to determine the fermentation kinetics of ruminant feeds. *Anim Feed Sci Technol* **48**:185–197 (1994).

13 Menke KH and Steingass H, Estimation of the energetic feed value obtained from chemical analysis and *in vitro* gas production using rumen fluid. *Anim Res Dev* **28**:7–55 (1988).

14 France J, Dhanoa MS, Theodorou MK, Lister SJ, Davies DR and Isac D, A model to interpret gas accumulation profiles associated with *in vitro* degradation of ruminant feeds. *J Theor Biol* **163**:99–111 (1993).

15 France J, Dijkstra J, Dhanoa MS, López S and Bannink A, Estimating the extent of degradation of ruminant feeds from a description of their gas production profiles observed *in vitro*: derivation of models and other mathematical considerations. *Br J Nutr* **83**:143–150 (2000).

16 Van Soest PJ, Wine RH and Moore LA, Estimation of the true digestibility of forages by the in-vitro digestion of cell walls, in *Proceedings of 10th International Grassland Congress*. Finnish Grassland Association, Helsinki, pp 438–441 (1966).

17 Steel RGD and Torrie JH, *Principles and Procedures of Statistics*. McGraw-Hill, New York (1980).

18 Everitt BS, Landau S and Leese M, *Cluster Analysis*, 4th edn. Edward Arnold, London (2001).

19 Getachew G, Makkar HPS and Becker K, The *in vitro* gas coupled with ammonia measurement for evaluation of nitrogen degradability in low quality roughages using incubation medium of different buffering capacity. *J Sci Food Agric* 77:87–95 (1998).

20 Ovejero FJ, Energía digestible y metabolizable de las pajas de leguminosas para los óvidos. *Anal Fac Vet León* **13**:307–354 (1967).

21 Mulholland JG, Coombe JB and Dann PR, Use of oat, lupin and field pea stubbles by grazing sheep. *Aust J Exp Agric Anim Husb* **16**:467–471 (1976).

22 Arnold GW and Wallace SR, The comparative nutritive value for weaner sheep of stubble and grain pea, vetch and lupin crops. *Aust J Agric Res* **28**:143–154 (1977).

23 Makkar HPS, Goodchild AV, Abd El-Moneim AM and Becker K, Cell-constituents, tannin levels by chemical and biological assays and nutritional value of some legume foliage and straws. *J Sci Food Agric* **71**:129–136 (1996).

24 Hadjipanayiotou M, Chemical composition, digestibility and *in situ* degradability of narbon vetch grain and straw grown in a Mediterranean region. *Annals de Zootechnie* **49**:475–478 (2000).

25 Haddad SG and Husein MQ, Nutritive value of lentil and vetch straws as compared with alfalfa hay and wheat straw for replacement ewe lambs. *Small Ruminant Res* **40**:255–260 (2001).

26 Flachowsky G, Tiroke K and Schein G, Botanical fractions of straw of 51 cereal varieties and *in sacco* degradability of various fractions. *Anim Feed Sci Technol* **34**:279–289 (1991).
27 Mould FL, Hervás G, Owen E, Wheeler TR, Smith NO and Summerfield RJ, The effect of cultivar on the rate and extent of combining pea straw degradability examined *in vitro* using the Reading pressure technique. *Grass Forage Sci* **56**:374–382 (2001).
28 Thomson EF, Herbert F and Rihawi S, Effects of genotype and simulated rainfall on the morphological-characteristics, chemical-composition and rumen degradation of the straw fractions of barley plants. *Anim Feed Sci Technol* **44**:191–208 (1993).
29 Mathison GW, Soofi-Siawash R, Okine EK, Helm J and Juskiw P, Factors influencing composition and ruminal degradability of barley straw. *Can J Anim Sci* **79**:343–351 (1999).
30 Bhargava PK, Ørskov ER and Walli TK, Rumen degradation of straw. 4. Selection and degradation of morphological components of barley straw by sheep. *Anim Prod* **47**:105–110 (1988).
31 Tolera A and Sundstøl F, Morphological fractions of maize stover harvested at different stages of grain maturity and nutritive value of different fractions of the stover. *Anim Feed Sci Technol* **81**:1–16 (1999).
32 Agbagla-Dohnani A, Noziere P, Clement G and Doreau M, *In sacco* degradability, chemical and morphological composition of 15 varieties of European rice straw. *Anim Feed Sci Technol* **94**:15–27 (2001).
33 Wilson JR, Cell wall characteristics in relation to forage digestion by ruminants. *J Agric Sci, Camb* **122**:173–182 (1994).
34 Chesson A, Mechanistic models of cell wall degradation, in *Forage Cell Wall Structure and Digestibility*, ed by Jung HG, Buxton DR, Hatfield RD and Ralph J. ASA–CSSA–SSSA, Madison, WI, pp 347–376 (1993).
35 Wilson JR and Hatfield RD, Structural and chemical changes of cell wall types during stem development: consequences for fibre degradation by rumen microflora. *Aust J Agric Res* **48**:165–180 (1997).
36 Carro MD, López S, González JS and Ovejero FJ, The use of the rumen degradation characteristics of hay as predictors of its voluntary intake by sheep. *Anim Prod* **52**:133–139 (1991).
37 Hall MB, Lewis BA, Van Soest PJ and Chase LE, A simple method for estimation of neutral detergent-soluble fibre. *J Sci Food Agric* **74**:441–449 (1997).
38 Blümmel M, Makkar HPS and Becker K, *In vitro* gas production: a technique revisited. *J Anim Physiol Anim Nutr* **77**:24–34 (1997).
39 Broudiscou LP, Agbagla-Dobnani A, Papón Y, Cornu A, Grenet E and Broudiscou AF, Rice straw degradation and biomass synthesis by rumen micro-organisms in continuous culture in response to ammonia treatment and legume extract supplementation. *Anim Feed Sci Technol* **105**:95–108 (2003).