Asian-Aust. J. Anim. Sci.
Vol. 22, No. 9 : 1256 - 1266
September 2009

www.ajas.info

Effects of Rice Straw Particle Size on Chewing Activity, Feed Intake, Rumen Fermentation and Digestion in Goats

X. G. Zhao[a], M. Wang[a], Z. L. Tan*, S. X. Tang, Z. H. Sun, C. S. Zhou and X. F. Han
Key Laboratory of Agro-ecological Processes in Subtropical Region,
Huanjiang Observation & Research Station of Karst Agro-ecosystem,
Institute of Subtropical Agriculture, the Chinese Academy of Sciences,
Changsha P.O. Box 10, Hunan 410125, China

ABSTRACT : Effects of particle size and physical effective fibre (peNDF) of rice straw in diets on chewing activities, feed intake, flow, site and extent of digestion and rumen fermentation in goats were investigated. A 4×4 Latin square design was employed using 4 mature Liuyang black goats fitted with permanent ruminal, duodenal, and terminal ileal fistulae. During each of the 4 periods, goats were offered 1 of 4 diets that were similar in nutritional content but varied in particle sizes and peNDF through alteration of the theoretical cut length of rice straw (10, 20, 40, and 80 mm, respectively). Dietary peNDF contents were determined using a sieve for particle separation above 8 mm, and were 17.4, 20.9, 22.5 and 25.4%, respectively. Results showed that increasing the particle size and peNDF significantly ($p<0.05$) increased the time spent on rumination and chewing activities, duodenal starch digestibility and ruminal pH, and decreased ruminal starch digestibility and NH_3-N concentration. Intake and total tract digestibility of nutrients (i.e. dry matter, organic matter, and starch) and ruminal fermentation were not affected by the dietary particle size and peNDF. Increased particle size and peNDF did not affect ruminal fibre digestibility, but had a great impact on the intestinal and total tract fibre digestibility. The study suggested that rice straw particle size or dietary peNDF was the important influential factor for chewing activity, intestinal fibre and starch digestibility, and ruminal pH, but had minimal impact on feed intake, duodenal and ileal flow, ruminal and total tract digestibility, and ruminal fermentation. (**Key Words :** Particle Size, Physical Effective NDF, Goat, Chewing, Digestibility, Ruminal pH)

INTRODUCTION

In the modern ruminant industry, feeding regimes are gradually changing to diets containing a relatively high proportion of concentrate to meet the increasing energy requirements of intensively managed animals. Dietary fibre is an essential nutrient in feeds and useful for the maintenance of normal rumen function, which has been associated with adequate salivation, optimal pH for cellulolytic microorganisms and energy supply (Allen, 1997; Yang et al., 2001b; Beauchemin and Yang, 2005; Tafaj et al., 2005b). However, sufficient dietary NDF without a sufficient proportion of long particles could elicit metabolic disorders (Plaizier et al., 2008). The concept of physically effective fibre (peNDF) was developed to combine into a single measurement both the NDF concentration and the physical form of a feed (Armentano and Pereira, 1997; Mertens, 1997). Many studies carried out on the effect of peNDF in ruminants were on dairy cattle (Moon et al., 2004). Goats have different feeding behavior, level of intake and rate of eating from cattle and other ruminant species, but have hardly received equal attention (Reid et al., 1990; Lu et al., 2005). It has thus become imperative to systemically investigate the effect of different fibre particle sizes in the diet of goats.

Hybrid rice is the most widely grown cereal crop in China, and rice straw is an important feed source for goat production by smallholders. Our previous investigations revealed that increasing proportions of rice straw increased the dietary NDF, but decreased the utilization of nutrients by growing goats (Zhao et al., 2007). However, as an important factor affecting the peNDF level in diets, the effects of particle size of rice straw in ruminant animals has rarely been reported. Information on other feedstuffs (i.e. barley straw, alfalfa forage, corn straw, and etc.) may not be easily applicable to rice straw, because of differences in

* Corresponding Author: Z. L. Tan. Tel: +86-7314619702, Fax: +86-7314612685, E-mail: zltan@sia.ac.cn
[a] The authors contributed equally to this work as co-first author.
Received December 4, 2008; Accepted April 4, 2009

chemical composition and physical form of fibre (Mertens, 1997; Plaizier et al., 2008).

The peNDF content of a feed is calculated as its NDF content multiplied by the physically effective factor (pef), which is determined by the cumulative material retained (DM basis) on a sieve with an aperture of 1.18 mm (Mertens, 1997). Although that system has been widely employed in many studies (Krause et al., 2002b; Beauchemin et al., 2003; Yang and Beauchemin, 2006a), it might not be adequately validated with the presence of different proportions of very long and intermediate length particles (Leonardi et al., 2005). It is still unclear which measure of peNDF and what peNDF contents provide the most accurate estimation (Yang and Beauchemin, 2006c). Furthermore, relationships between peNDF and cattle response (i.e. chewing activity, ruminal fermentation and digestion) are still inconsistent because of differences in measuring peNDF (Yang et al., 2001a; Beauchemin et al., 2003; Yansari et al., 2004).

To improve understanding of peNDF on ruminants, our initial objectives were to determine appropriate peNDF measurement of different particle sizes in rice straw for its application in small ruminants, and then reveal the relationship between dietary peNDF and response (i.e. chewing activity, ruminal fermentation and digestibility), and the related underlying mechanisms under the present house-feeding regimes used by smallholders for goats.

MATERIALS AND METHODS

Animals and their management

A 4×4 Latin square experiment with 4 mature Liuyang black male goats (a local breed, body weight of 24.7±1.4 kg) was conducted. The goats were surgically fitted with ruminal, proximal duodenal and terminal ileal fistulae. About 30 d were allowed for animal recovery following surgery. The use of the animals and the experimental procedure were approved by the Animal Care Committee, Institute of Subtropical Agriculture (ISA).

Rice straw (Hybrid rice Teyou 640, released by Hunan Academy of Agricultural Sciences) was harvested at a moisture content of about 30% from a single field and then sun-dried to 15% moisture content. The straw was chopped with a hay cutter to theoretical cut length (TCL) of 10, 20, 40 and 80 mm for the preparation of four dietary treatments (i.e. short, medium1, medium2 and long) (Table 1), based on the assumption that fiber in long feed particles (>10 mm) promotes chewing and saliva secretion, and would help to neutralize the acids produced during ruminal digestion of feeds (Beauchemin and Yang, 2005). Because of low contents of metabolisable energy and protein of rice straw, the diets were formulated to contain 40% rice straw and 60% concentrate to meet 1.3 times maintenance requirements of the experimental goats (Table 2). The four diets were of the same chemical composition to ensure that the difference in dietary peNDF content came from the particle size of rice straw. The feed was offered in two equal portions at 08:00 and 20:00 h. The amount of diet offered to each goat was restricted to 90% of its *ad libitum* intake to ensure that there was no remnant during the whole experimental period. All goats had free access to fresh water, and were kept individually in stainless steel metabolism cages in a temperature-controlled (20°C) and constantly lighted house.

Table 1. Mean particle size, physical effective factor (pef), and physically effective fiber (peNDF) content of rice straw[1]

Item	Particle size				SEM	p
	Short	Medium1	Medium2	Long		
% DM retained on sieves						
44.00 mm	0.82^{d}	25.7^{c}	47.5^{b}	56.15^{a}	0.18	0.01
22.00 mm	37.6^{b}	39.6^{a}	30.4^{d}	33.46^{c}	0.41	0.01
8.00 mm	26.5^{a}	12.7^{b}	5.7^{c}	5.67^{c}	0.38	0.01
3.50 mm	18.4^{a}	7.7^{b}	7.3^{b}	2.15^{c}	0.17	0.01
2.00 mm	15.1^{a}	10.7^{b}	7.2^{c}	1.84^{d}	0.23	0.01
1.50 mm	0.35^{c}	3.2^{a}	0.96^{b}	0.42^{c}	0.07	0.01
1.18 mm	0.73^{a}	0.12^{b}	0.65^{a}	0.14^{b}	0.07	0.01
<1.18 mm	0.35^{a}	0.26^{b}	0.23^{b}	0.15^{c}	0.02	0.01
$pef_{>8}$	0.65^{d}	0.78^{c}	0.84^{b}	0.95^{a}	0.01	<0.01
$peNDF_{>8}$ (% DM)	43.4^{d}	52.1^{c}	55.9^{b}	63.7^{a}	0.07	<0.01
$pef_{>1.18}$	0.996	0.997	0.998	0.998	0.01	NS
$peNDF_{>1.18}$ (% DM)	66.6	66.7	66.7	66.8	0.01	NS

[1] Particle size distribution of rice straw was measured by dry sieving using a vertical oscillating sieve shaker with a stack of sieves arranged in descending mesh size. $pef_{>8}$ and $pef_{>1.18}$ physical effectiveness factor based on the proportion of cumulative DM retained above 8 and 1.18 mm sieve respectively. $peNDF_{>8}$ and $peNDF_{>1.18}$ physical effective NDF determined as NDF content of rice straw multiplied by pef_8 and $pef_{1.18}$ respectively.
Means with different letters within a column are significantly different ($p<0.05$); NS means no significant difference.

Table 2. The dietary ingredients and chemical composition [1]

Item	Diet			
	Short	Medium1	Medium2	Long
Ingredients (%)				
Rice straw, TCL by 10 mm	40.0	0	0	0
Rice straw, TCL by 20 mm	0	40.0	0	0
Rice straw, TCL by 40 mm	0	0	40.0	0
Rice straw, TCL by 80 mm	0	0	0	40.0
Corn meal	37.0	37.0	37.0	37.0
Soybean meal	9.4	9.4	9.4	9.4
Wheat bran	8.0	8.0	8.0	8.0
Rape-seed meal	2.0	2.0	2.0	2.0
urea	0.8	0.8	0.8	0.8
Premix[2]	2.0	2.0	2.0	2.0
Chemical composition				
ME [3] (MCal/kg DM)	2.24			
Dry matter (%)	89.4			
Crude protein (%)	13.8			
Ca (%)	0.28			
Phosphorus (%)	0.27			
Neutral detergent fiber (%)	35.2			
Acid detergent fiber (%)	22.3			
$pef_{>8}$[4]	0.49	0.59	0.63	0.72
$peNDF_{>8}$[5] (%DM)	17.4	20.9	22.5	25.4

[1] Values, expressed on a dry matter basis.

[2] Premix contained per kilogram: 119 g $MgSO_4 \cdot H_2O$, 2.5 g $FeSO_4 \cdot 7H_2O$, 0.8 g $CuSO_4 \cdot 5H_2O$, 3 g $MnSO_4 \cdot H_2O$, 5 g $ZnSO_4 \cdot H_2O$, 10 mg Na_2SeO_3, 40 mg KI, 30 mg $CoCl_2 \cdot 6H_2O$, 95,000 IU vitamin A, 17,500 IU vitamin D, and 18,000 IU vitamin E.

[3] ME = Metabolizable energy, calculated by the data of Zhang and Zhang (1998).

[4] $pef_{>8}$, determined as the proportion of DM retained on the 8 mm sieve.

[5] $peNDF_{>8}$ was measured as the NDF content of TMR (total mixed ration) multiplied by the $pef_{>8}$.

The experiment consisted of 4 periods, and each period lasted for 26 d, consisting of a 12 d adaptation period and 14 d for data and sample collection. The amount of feed offered was weighed and recorded daily during the last 14 d to calculate the feed intake. Samples of rice straw and concentrate TMR (total mixed ration) were collected daily, mixed into one sample per goat, and dried at 65°C for 48 h for the determination of nutrient intake and digestibility.

Particle size separation

Particle size distribution of rice straw and TMR was determined with the aid of a horizontal oscillating particle separator containing seven screen sizes (44.0, 22.0, 8.0, 3.5, 2.0, 1.5 and 1.18 mm) and a pan (Table 1). Approximately 200 g feed was placed into the top sieve screen, and the stack of sieves was shaken until there were no more changes in the distribution of materials for approximately 10 minutes. The sieve set was horizontally shaken backward, forward and rotated. The shaking frequency was 2 Hz. Particles were prevented from being stacked upon each other. Particles retained on the different screen sizes were then collected, dried at 65°C for 48 h and weighed. The peNDF content was calculated as the NDF content of feeds or TMR multiplied by the physically effective factor (pef), which was determined by the cumulative material retained (DM basis) on each sieve. The $peNDF_{>8}$ and $peNDF_{>1.18}$ were selected according to the standard peNDF for dairy cows to simplify our initial study. Four dietary $peNDF_{>8}$ levels were determined.

Chewing activity

Eating and ruminating activities of the four goats were monitored visually for 24 h from the 25th to 26th day, noted and recorded every 5 min. Each activity was assumed to persist for the entire 5 min interval. Eating was defined as at least 1 min of eating activity after at least 20 min without eating activity. A period of rumination was defined as at least 5 min of rumination occurring after at least 5 min without ruminating activity. Average daily intake was used to estimate the time spent eating or ruminating per gram of dry matter intake (DMI), neutral detergent fiber intake (NDFI) and acid detergent fiber intake (ADFI). Eating and rumination activities were expressed as total minutes for the 24 h period or on the basis of DMI, NDFI and ADFI by dividing minutes of eating or ruminating by intake. Chewing activities were calculated as the sum of eating and ruminating activities.

Site and extent of nutrient digestion

Duodenal and ileal flows and apparent digestibility of nutrients in the total tract or at different sites of the digestive tract were determined using Cr_2O_3 as a digesta flow maker according to procedures described previously (Tan et al., 2001; Tan et al., 2002). One gram Cr_2O_3 was dosed through the rumen cannula at 06:00, 12:00, 18:00 and 24:00 h (total of 4 g of Cr_2O_3/d) from 13 to 20 d with a priming dose of 2 g at 06:00 on day 13 (total of 5 g of Cr_2O_3/d). Approximately 30 ml duodenal and ileal contents were collected at 09:00, 15:00, 21:00 and 03:00 at 18 d, at 07:00, 13:00, 19:00, and 01:00 at 19 d and at 05:00, 11:00, 17:00 and 23:00 at 20 d. This schedule provided 12 representative samples of duodenal and ileal contents taken at 2 h intervals. Samples were immediately subsampled, composited across sampling times for each goat and each period, dried at 65°C, ground to pass a 1 mm sieve and stored for chemical analysis.

Samples of faeces were collected daily from each goat quantitatively from 16 to 20 d with the aid of collection bags tied to the rear of the goats. Accumulated faeces were removed and weighed at 24 h intervals for 5 d, and 10% representative samples were retained and stored at -20°C for chemical analysis. The duodenal and ileal flows, and apparent digestibility of nutrients were calculated according to the procedure modified by Tan et al. (2002). Total apparent nutrient digestibility was calculated according to the difference between nutrient intake and faecal output.

Ruminal pH and fermentation

Ruminal pH and fermentation were monitored from 21 to 22 d. Ruminal fluid samples (50 ml) were taken with a rumen filter probe tube via the ruminal cannula at 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 h after the morning feeding on day 21 of each period. The pH values of the ruminal fluid samples were recorded using a pH meter (REX, Shanghai instrument factory, pHS-3C). Samples were immediately squeezed through 4 layers of cheesecloth with a mesh size of 250 μm. Filtered ruminal fluid (10 ml) was centrifuged at 20,000 g for 15 min at 4°C to obtain a clear supernatant, and then analyzed for ammonia using a phenol-hypochlorite assay.

For the determination of the volatile fatty acid (VFA) content, 10 ml of ruminal fluid was centrifuged at 500 g for 10 min at 4°C to obtain a clear supernatant. The solution was then put into a plastic bottle containing 1 ml of 25% metaphosphoric acid and 1 ml of 0.6% 2-ethyl butyric acid (internal standard). The fluid mixture was centrifuged at 20,000 g for 15 min at 4°C to obtain a clear supernatant which was stored at -20°C for subsequent analysis.

Chemical analysis

Neutral detergent fibre and acid detergent fibre were determined using the methods of Van Soest et al. (1991). Neutral detergent fibre was assayed with the addition of a heat stable amylase, but without sodium sulphite, and was expressed inclusive of residual ash. Acid detergent fibre was expressed inclusive of residual ash. Dry matter (DM), organic matter (OM), starch and crude protein (CP) of all samples was determined according to AOAC (2002). The Cr concentration was analyzed by atomic absorption spectroscopy (Model 932AA, GBC Scientific Equipment Pty Ltd, Australia) according to the instruction of Williams et al. (1962).

The ruminal bacteria pellets and about 150 ml lyophilized duodenal digesta were analyzed for concentration of diaminopimelic acid (DAPA) as described by Olubobokun et al. (1988). The ratios of DAPA to bacteria OM were determined for ruminal microbial pellets. The duodenal flows of OM were calculated by multiplying the ratios of DAPA to bacteria OM and the duodenal DAPA concentration.

Ammonia was analyzed by a phenol-hypochlorite assay (Chaney and Marbach, 1962). The VFA were separated on a packed column (model SP-1200, Supelco, Bellefonte, PA) with 2-ethyl butyric acid as the internal standard, and quantified by gas chromatography (Hewlett Packard 5890, HP, USA).

Statistical analysis

All data were analyzed as a 4×4 Latin square design using the GLM procedure of SAS (1996). The model used was: $Y_{ijkl} = \mu+G_i+P_j+T_k+e_{ijkl}$ where μ is overall mean, G_i is effect of goat (i = 1 to 4), P_j is effect of period (j = 1 to 4), T_k is fixed effect of treatment (k = 1 to 4), and e_{ijkl} is residual error. Where the treatment effect was significant, differences among means were tested with Duncan's multiple range test. Statistical significances were considered to exist if $p<0.05$. Orthogonal polynomial contrasts were used to examine the responses (linear and quadratic) to an increase in the levels of peNDF in the diets. In orthogonal polynomial analysis, coefficients were corrected because of unequal spacing of treatments.

RESULTS

Physically effective fiber (peNDF)

The values of pef and peNDF above 8 mm sieves were lower than the corresponding values of above 1.18 mm sieves. The $pef_{>8}$ of rice straw was in much larger range than its $pef_{>1.18}$ (range of 0.65 to 0.95 vs. 0.996 to 0.998). As a result, the range of $peNDF_{>8}$ was greater than that of

Table 3. The effects of dietary rice straw particle size levels on the chewing activity in goats (n = 4)[1]

Item	Diet				SEM	Effects[2]	
	Short	Medium1	Medium2	Long		L	Q
Eating							
min/d	135	131	136	154	7.18	0.12	0.15
min/g DMI	0.24	0.23	0.24	0.27	0.02	0.20	0.27
min/g NDFI	0.64	0.61	0.65	0.73	0.05	0.24	0.23
min/g ADFI	0.95	0.89	0.94	1.08	0.07	0.26	0.23
Rumination							
min/d	252^{b}	264^{ab}	294^{ab}	309^{a}	13.9	0.02	0.74
min/g DMI	0.44^{c}	0.46^{bc}	0.53^{ab}	0.55^{a}	0.02	0.01	0.82
min/g NDFI	1.20^{c}	1.22^{bc}	1.41^{ab}	1.47^{a}	0.06	0.01	0.57
min/g ADFI	1.75^{b}	1.78^{b}	2.05^{ab}	2.16^{a}	0.08	0.01	0.49
Chewing							
min/d	387^{b}	395^{b}	429^{ab}	463^{a}	15.9	0.01	0.34
min/g DMI	0.68^{b}	0.69^{b}	0.77^{ab}	0.82^{a}	0.03	0.02	0.45
min/g NDFI	1.84^{b}	1.83^{b}	2.05^{ab}	2.21^{a}	0.09	0.02	0.30
min/g ADFI	2.70^{b}	2.67^{b}	3.00^{ab}	3.24^{a}	0.13	0.02	0.27

[1] DMI, NDFI, ADFI and SEM were dry matter per day, neutral detergent fiber per day, acid detergent fiber per day and pooled standard error of means, respectively.
[2] Linear (L) and quadratic (Q) effects were tested in relation to the peNDF content of diets.
Means with different letters within a column are significantly different (p<0.05).

$peNDF_{>1.18}$ (range of 43.4% to 63.7% vs. 66.6% to 66.8%). By further examining the details of particle size distribution in the horizontal oscillating sieve shaker, there existed significant differences (p<0.01 or p = 0.01) between the DM retained on each sieve size, especially for the 44 mm sieve.

Chewing activities

Time for eating activity showed an increased numerical trend with increased TCL level (Table 3). The numerically increasing trends were also observed with increased TCL in terms of per kg of DMI, NDFI and ADFI. Furthermore, there existed no linear or quadratic relationships between TMR peNDF level and eating activities.

Time for rumination or chewing activity showed a significant increase with the elevated TCL level. The same results were observed when the time spent eating was expressed as variables of eating efficiency and chemical composition (i.e. per kg of DMI, NDFI and ADFI). Furthermore, there existed significant positive linear relationships (p<0.05) between TMR peNDF level and time of rumination or chewing activities.

Feed intake, duodenal and ileal flows

Particle size with increased TCL of rice straw did not affect the intake of goats (Table 4). Furthermore, no significant linear or quadratic relationships were observed between peNDF and intake. The duodenal flows (i.e. DM, OM, NDF and ADF) were not significantly affected by the increased particle size of rice straw (Table 4). However, the duodenal flow of starch was significantly higher in medium1, medium2 and long diets. No significant linear relationships between peNDF of TMR and duodenal nutrition flows were observed, except for starch. Microbial OM (MOM) flow was significantly (p<0.01) higher in medium1 treatment, when compasred with short treatment. The ileal flows of DM, OM and starch were not significantly affected by the increased particle size of rice straw (Table 4). However, the duodenal flows of NDF and ADF were significantly (p<0.05) higher in medium1. There were no significant linear or quadratic relationships between peNDF of TMR and the ileal flow.

Digestibility

The digestibilities of DM, OM, NDF and ADF in the rumen were similar with increasing particle size of rice straw without significant linear or quadratic relationships with peNDF of TMR (Table 5). However, starch digestibility in the rumen was significantly lower (p<0.05) in short level (TCL = 10 mm) than in the other three levels of TCL, and showed a negative linear relationship (p<0.01) with peNDF of TMR.

Particle size of rice straw greatly affected the intestinal digestibility of DM, OM, NDF and ADF. They were significantly lower (p<0.05) in medium2 (TCL = 40 mm), while starch intestinal digestibility was significantly higher (p<0.05) in short level (TCL = 10 mm) (Table 5). Significant linear relationships existed between peNDF of TMR and intestinal digestibility of DM (p = 0.05) and starch (p<0.01), while a significant quadratic relationship

Table 4. The effects of dietary rice straw particle size on the intake, and duodenal and ileal flow in goats (n = 4)[1]

Item	Diet				SEM	Effects[2]	
	Short	Medium1	Medium2	Long		L	Q
Intake (g/d)							
DM	568	575	554	569	10.2	0.82	0.77
OM	485	491	473	485	8.7	0.81	0.77
NDF	211	216	208	211	5.2	0.88	0.74
ADF	144	148	143	144	3.9	0.89	0.64
Starch	151	151	145	151	2.1	0.74	0.20
Duodenal flow (g/d)							
DM	288	297	260	284	9.84	0.42	0.57
OM	226	247	210	240	12.7	0.76	0.78
MOM	49.5[b]	54.4[a]	47.4[b]	47.1[b]	1.35	0.12	0.08
NDF	104	123	101	109	6.23	0.92	0.34
ADF	77.4	80.4	74.7	83.2	4.26	0.66	0.56
Starch	35.7[b]	46.2[a]	47.1[a]	54.5[a]	2.43	<0.01	0.70
Ileal flow (g/d)							
DM	130	134	128	141	11.0	0.59	0.66
OM	97.6	99.3	104	107	7.69	0.36	0.90
NDF	93.8[b]	112.3[a]	94.4[b]	90.8[b]	3.11	0.35	0.12
ADF	71.3[b]	85.6[a]	72.3[b]	75.9[b]	2.18	0.98	0.50
Starch	11.6	14.8	13.5	15.7	1.64	0.15	0.80

[1] DM, OM, MOM, NDF, ADF and SEM were dry matter, organic matter, microbial organic matter, neutral detergent fiber, acid detergent fiber and pooled standard error of means, respectively.

[2] Linear (L) and quadratic (Q) effects were tested in relation to the peNDF content of diets.

Means with different letters within a column are significantly different ($p<0.05$).

Table 5. Effect of dietary rice straw particle size on the site and extent of apparent digestion of nutrients in goats (n = 4)[1]

Item	Diet				SEM	Effects[2]	
	Short	Medium1	Medium2	Long		L	Q
Rumen (% intake)							
DM	49.2	48.3	52.9	50.0	1.86	0.52	0.70
OM	53.2	49.5	55.5	50.4	2.55	0.67	0.76
NDF	50.6	42.7	51.4	48.0	2.80	0.81	0.42
ADF	46.2	38.9	47.9	41.9	2.54	0.52	0.74
Starch	76.3[a]	69.2[b]	67.3[b]	63.9[b]	1.58	<0.01	0.42
Intestine (% intake)							
DM	27.8[a]	28.4[a]	24.0[b]	25.2[ab]	0.97	0.05	0.99
OM	26.6[ab]	30.2[a]	22.3[b]	27.4[a]	1.38	0.19	0.80
NDF	4.73[b]	4.28[b]	3.25[b]	7.93[a]	0.57	0.96	<0.01
ADF	5.36[ab]	3.56b[c]	2.18[c]	6.17[a]	0.52	0.83	<0.01
Starch	16.0[b]	20.9[ab]	23.2[a]	25.7[a]	1.56	<0.01	0.61
Total digestibility (% intake)							
DM	79.6	82.9	82.5	78.8	1.7	0.80	0.07
OM	82.6	85.0	81.6	80.0	1.4	0.18	0.17
NDF	56.9[b]	68.1[a]	65.6[a]	57.9[b]	2.5	0.92	0.03
ADF	46.1[ab]	54.8[a]	55.5[a]	45.0[b]	2.7	0.92	0.04
Starch	93.1	92.7	93.4	93.0	0.9	0.71	1.00

[1] DM, OM, MOM, NDF, ADF and SEM were dry matter, organic matter, microbe organic matter, neutral detergent fiber, acid detergent fiber and pooled standard error of means, respectively.

[2] Linear (L) and quadratic (Q) effects were tested in relation to the peNDF content of diets

Means with different letters within a column are significantly different ($p<0.05$).

($p<0.01$), or 'U' shape pattern, between peNDF of TMR and intestinal fibre (i.e. NDF and ADF) digestibility was observed.

The digestibility of DM, OM and starch in the total tract were similar across the increased particle sizes of rice straw without significant linear or quadratic relationships with peNDF of TMR (Table 5). Total tract NDF and ADF digestibilities were significantly higher ($p<0.05$) in medium1 and medium2, and had a significant quadratic relationship ($p<0.05$), or '∩' shape pattern, with peNDF of TMR.

Rumen pH and fermentation

Increasing rice straw particle size increased the ruminal pH and decreased ruminal NH_3-N concentration (Table 6). Ruminal pH showed a positive significant linear relationship ($p<0.01$) with peNDF of TMR, while ruminal NH_3-N concentration displayed a negative significant linear or quadratic relationship ($p<0.05$) with peNDF of TMR. Total ruminal VFA, acetate:propionate ratio, and individual VFA remained similar across the increased particle sizes of rice straw.

DISCUSSION

Physically effective fiber (peNDF)

The $peNDF_{>1.18}$ hardly effectively differentiated the peNDF content in four TCL levels, these particle size distribution patterns were in agreement with previous studies using the Penn state particle separator (PSPS) method, when a 1.18-mm sieve was used. For example, 99% of the sample was retained (Soita et al., 2005); 93-96% of samples for three TCL levels (4.8, 15.9, and 28.6 mm) were retained (Yang and Beauchemin, 2006c); no difference in pef was obtained for long (22.3 mm) and short (4.8 mm) cut corn silages (Kononoff and Heinrichs, 2003). There existed significant differences for DM retained on each sieve size, especially for the 44 mm sieve. This indicated that high proportions of long and intermediate length particles accounted for similar values of $pef_{>1.18}$ or $peNDF_{>1.18}$ in rice straw of four TCL levels. The pef and peNDF values above a 1.18 mm sieve hardly adequately reflect differences in particle length of rice straw. So, pef and peNDF values obtained above a 8 mm sieve (Table 2) were used to reveal the relationships between diet peNDF and animal response (i.e. chewing activity, rumen fermentation, and digestion) in this present study. Similar pef and peNDF values were also employed in several studies in dairy cows (Yansari et al., 2004; Zebeli et al., 2006). However, there is no report of a peNDF threshold for goats; it will be necessary to measure the passage rate and rumen fill for each particle size in our future studies.

Chewing activities

Goats spent 135-153 min/d (2.25-2.55 h/d) eating, 251-309 min/d (4.2-5.2 h/d) ruminating, and 386.8-463.5 min/d (6.45-7.75 h/d) chewing. Times spent eating, ruminating or chewing were lower in goats, when compared with cows (232-300 and 351-502 min/d for eating and ruminating, respectively) (Krause et al., 2002b), lactating dairy goats (176 to 325 and 267 to 486 min/d for eating and ruminating, respectively) (Santini et al., 1992) and crossbred goats (188 to 207 and 299 to 363 min/d for eating and ruminating, respectively) (Lu et al., 2005). It has been reported that body size alone accounts for more than 50% of variability in chewing activities recorded for ruminant animals. Larger body-sized animals tended to spend more time on chewing activities than those of small body size (Bae et al., 1979; Lu

Table 6. Effect of dietary rice straw particle size on the ruminal pH and fermentation in goats (n = 4) [1]

Item	Diet				SEM	Effect [2]	
	Short	Medium1	Medium2	Long		L	Q
Ruminal pH	6.02[c]	6.08[bc]	6.13[ab]	6.22[a]	0.03	<0.01	0.41
Ruminal NH_3-N (mg/dl)	24.1[a]	25.2[a]	23.1[a]	20.2[b]	0.77	0.01	0.03
Ruminal VFA							
Total (mmol)	97.3	95.5	90.8	86.2	4.39	0.11	0.84
Acetate:propionate	2.17	2.03	2.06	2.38	0.22	0.49	0.35
Individual VFA (% of total)							
Acetate	52.0	53.7	52.7	53.8	2.49	0.68	0.90
Propionate	24.9	27.5	27.4	23.4	1.48	0.42	0.07
Butyrate	16.8	13.3	14.6	17.4	1.37	0.61	0.06
Isobutyrate	1.90	1.60	1.66	1.63	0.12	0.22	0.29
Isovalerate	2.42	1.98	1.91	2.16	0.12	0.27	1.00
Valerate	1.93	1.90	1.76	1.70	0.15	0.22	0.03

[1] VFA and SEM were volatile fatty acids and pooled standard error of means.

[2] Linear (L) and quadratic (Q) effects were tested in relation to the peNDF content of diets.

Means with different letters within a column are significantly different ($p<0.05$).

et al., 2005). The smaller body size of the Liuyang black goat used in this study compared with other species might contribute to the variation in eating, ruminating and chewing time.

Particle size of rice straw or TMR peNDF hardly affected the eating activities in goats. Similar results were reported in cows fed diets containing different kinds of forages (Krause et al., 2002b; Yang and Beauchemin, 2006b; Zebeli et al., 2007). There existed significant positive linear relationships between TMR peNDF level and variables of rumination or chewing activities (Tafaj et al., 2005; Zebeli et al., 2006). Ruminating and total chewing activities are associated with increased saliva output, which plays an essential role in buffering acids produced during rumen fermentation and in stabilizing rumen pH (Allen, 1997). Results from this study showed that increased particle size of rice straw or TMR peNDF (particle size>8 mm) significantly increased ruminating and chewing activities in goats. The increased chewing activity might be a function of maintaining rumen characteristics, which were affected by degree and rate of ruminal digestion.

Feed intake

The DM intake of goats ranged from 567.8-568.6 g/d, which was a little higher than the 506-507 g/d observed previously (Zhao et al., 2007). The increased feed intake was due to the increased proportion of rice straw in the TMR (Zhao et al., 2007). This study corroborated results from elsewhere on the effects of particle size on feed intake. For instance, Yang et al. (2001b) and Beauchemin and Yang (2005) reported that reducing forage particle size had no effect on intake. However, some studies reported positive effects of reduced particle size on DMI and NDFI (Schwab et al., 2002; Kononoff et al., 2003). Feed intake was influenced by ruminal digestion profile (i.e. digestion rate and passage rate of feeds), or some physiological factors of blood biochemical parameters (Sunagawa et al., 2007a,b) Although long particle size of feed increases the passage rate of feed from the rumen, feed intake might thereby remain the same for different digestion rates (Yang and Beauchemin, 2006b). Furthermore, chewing activity influences the relationship between dietary peNDF and passage rate of feeds out of the rumen (Beauchemin and Yang, 2005). A conclusion could be drawn that there are no fixed relationships between particle size and feed intake in ruminant animals (Tafaj et al., 2007). Studies in dairy cattle concluded that metabolic, rather than physical, constraint was typically rate-limiting of feed intake (Allen, 2000; Yang and Beauchemin, 2006b).

Duodenal and ileal flow

Duodenal flows (Table 5) were similar to the range reported previously by Zhao et al. (2007) (i.e. DM, 260.3-288.5 g/d vs. 283.4-249.6 g/d), while ileal flows were slightly lower than previously reported (i.e. DM, 127.6-141.2 g/d vs. 167.9-193.6 g/d).

Duodenal flows of DM, OM, NDF and ADF were not affected by increased particle size of rice straw. It has earlier been reported that duodenal flows were not affected by different treatments of physically effective fibre in dairy cows (Yang et al., 2000; Yang and Beauchemin, 2005). There was a significant linear relationship between peNDF of TMR and duodenal starch flow. Re´mond et al. (2004) reported a significant linear relationship between corn particle size and duodenal starch flow. No significant relationship was observed between peNDF of TMR and MOM flow, and this was in agreement with the report of Yang and Beauchemin (2005).

Digestibility

When compared with our previous results (Zhao et al., 2007), ruminal OM digestibility was not significantly different with increased proportions of rice straw in the TMR (i.e. 50.4-55.5% vs. 51.2 -56.5%), but the intestinal and total tract OM digestibility (i.e. 22.3-30.2% vs. 13.1-15.2% and 80.0-85.0% vs. 69.3-73.7%) were slightly higher. Increased digestibility in the intestine accounted for the increased total tract digestibility in the present study. Similar digestibility in the rumen (i.e. DM, OM, NDF and ADF) across the different TCL levels was in agreement with previous studies with cows, except for starch (Yang et al., 2002; Yang and Beauchemin, 2005). In this study, ruminal starch digestibility showed a significant negative linear relationship with peNDF of the TMR.

The intestinal digestibility of nutrients was inconsistent with previous studies, which indicated that digestibility in the intestine was not affected by dietary peNDF levels (Yang et al., 2002; Yang and Beauchemin, 2005), but numerical effects of increased dietary peNDF on increased NDF digestibility were observed in the intestine. Significantly higher fiber digestibility was also observed on the long diet (TCL = 80 mm) than on other diets. Galyean and Defoor (2003) reported that peNDF content affects ruminal starch digestion, and should be within the normal range of roughage levels used in feedlot diets. In the present study, increased particle size reduced starch digestibility in the rumen and increased starch digestibility in the intestine.

The unchanged DM, OM and starch digestibility in the total tract across four TCL levels was in agreement with previous studies in cows (Jaster and Murphy, 1983; Krause et al., 2002a). Although it was assumed that increased dietary peNDF or forage particle size tended to increase NDF digestibility in the total tract (Shaver et al., 1986; Woodford and Murphy, 1988), no significant relationship between peNDF and NDF digestibility in the total tract was reported (Krause et al., 2002a; Yand and Beauchemin, 2005). The significant quadratic effect of increased particle size of rice straw on NDF digestibility in the total tract was also observed in this study.

Rumen pH and fermentation

Ruminal pH is a very important variable to indicate function of the rumen ecosystem. The incidence of sub-acute acidosis increased when ruminal pH fell below 5.8 (Krause and Oetzel, 2006; Tafaj et al., 2007). The ruminal pH range of 6.02 to 6.22 reported in this study was within the normal function of the rumen ecosystem. It was slightly lower than in our previous study (pH range 6.21-6.39) in goats (unpublished data). It indicated that increased rice straw proportion of the TMR would increase the ruminal pH in goats.

Ruminal pH was significantly increased by the increased particle size of rice straw or peNDF of TMR. One of the most important factors influencing rumen pH is the amount of saliva buffer secretion, which is positively correlated with rumination activity (Lu et al., 2005; Zebeli te al., 2008). In this study, ruminal pH pattern corresponded to the increased time of rumination and chewing activity. The underlying mechanism has been proposed that increasing particle size or peNDF increases rumination activity, then increases the salivary secretion flow into the rumen, and thus buffers the ruminal pH (Krause et al., 2002b; Beauchemin et al., 2003). This indicates that adequate forage particle size or effective fiber is very important for maintaining normal rumen ecosystem function. Lack of forage particle size or effective fibre in the TMR might cause ruminal acidosis. In addition, the decreased digestibility of starch in the rumen was another primary factor for the higher ruminal pH in our study, because starch fermentation in the rumen might appear to have larger effects on pH than the physical characteristics of feeds (Yang et al., 2001b).

Increased particle size of rice straw decreased the ruminal NH_3-N concentration. This was inconsistent with previous studies which indicated that particle size had no significant effect on ruminal NH_3-N concentration (Yansari et al., 2004; Zebeli et al, 2008). No significant effects of increased particle length on total VFA concentration acetate:propionate ratio, and individual VFA concentration were observed in this study.

IMPLICATIONS

When rice straws were chopped with a hay cutter for theoretical cut length of 10, 20, 40 and 80 mm, pef and peNDF values above a 1.18 mm sieve did not adequately reflect particle size differences. The pef and peNDF values obtained above a 8 mm sieve were employed in this study. Particle size and peNDF increased the time of rumination and chewing activity, but showed no impact on feed intake. Ruminal pH was increased because of increased time spent in rumination and decreased digestibility of starch in the rumen for an increased particle size or peNDF. Particle size and peNDF may protect starch escaping digestion in rumen and promote the efficiency of metabolisable energy in goats, because of decreased rumen starch digestibility and increased intestinal starch digestibility. Although elevated rumen pH tended to favor the growth of cellulolytic microbes, decreased rumen NH_3-N concentration (an important N source for cellulolytic bacteria) could reduce ruminal microbial protein synthesis. The integrated effect of increased rumen pH and decreased rumen NH_3-N concentration caused a similar ruminal fermentation (i.e. total VFA concentration, acetate:propionate ratio and individual VFA concentration), and thus resulted in a similar ruminal OM and fibre digestibility across the increased particle sizes. Further studies are needed to systematically reveal the effect of particle size and peNDF in goats, such as on N metabolism, blood biochemical parameters and microbial amino acid profile.

ACKNOWLEDGMENTS

The authors would like to thank the Knowledge Innovation Program of CAS (Grant No. Kscx2-Yw-N-022 & KZCX2-XB2-08), and Realm Frontier Project of ISA (Grant No. 0751012010) for the joint financial support.

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