Effect of steam explosion on \textit{in vitro} gas production kinetics and rumen fermentation profiles of three common straws

Li Wen He, Qing Xiang Meng, De Yong Li, Fei Wang, Li Ping Ren
College of Animal Science and Technology, China Agricultural University, Beijing, China

Abstract

To investigate the effect of steam explosion on \textit{in vitro} gas production (GP) and rumen fermentation profiles of common straws, \textit{in vitro} cultivation was conducted for 96 h with the rumen fluid collected from steers. Different types of straw had various chemical compositions, which were affected by steam explosion (P<0.01). Steam explosion increased (P<0.01) the rate and volume of GP, lag time disappeared and asymptotic GP decreased, which were also affected (P<0.01) by the type of straw. The type of straw influenced (P<0.05) the final pH, while steam explosion exerted an effect (P<0.01) on the ammonia-nitrogen concentration. The proportions of individual volatile fatty acid (VFA), except acetate (A), differed (P<0.05) among the feeds. Steam explosion increased total VFA production and the proportion of propionate (P), while decreased the proportions of A, iso-butyrate and valerate as well as the ratio A/P (P<0.01). The type of straw had an effect (P<0.05) on the activities of avicelase and carboxymethyl cellulase (CMCase), while steam explosion increased (P<0.01) the activities of avicelase, CMCase, β-glucanase and xylanase. The available energy concentrations and digestibilities differed (P<0.01) in the feeds and were increased (P<0.05) with steam explosion processing. The interaction straw type×treatment was significant (P<0.05) for most monitored parameters. These results suggest that steam explosion could improve rumen fermentability and energy utilisation of straw, being an effective pre-treatment method in feed industry.

Introduction

Given the circumstance of the lack of feed resources and the contradictory between feed and food supplies becoming increasingly severe in recent years, much interest has been devoted to the study of exploiting roughage resource. As the largest crops cultivated in the world (Asseng et al., 2011), straw derived from corn, rice and wheat is certainly huge-production, with the annual straw production of China alone exceeding 620 million tons (Zeng et al., 2007) and globally 600-900 million tons rice straw (Karimi et al., 2006). It could be considered as a great resource or source of pollution. As a byproduct, disposal of straw could be problematic for many districts. In practice, only a small portion of global straw is used in industry production or animal feeding, most is left in the field or burned (Sarkar et al., 2012). However, if effectively used as a primary feed-stuff for ruminants like beef cattle, straw could be an important renewable resource (Males, 1987). As the world demands the increases for grain supplies and livestock products, the economics and practicality of converting straw to more usable forms will become more crucial.

Researchers in animal nutrition have widely recognised the huge potential for straw as a feed resource and have been exploring its effective pretreatment methods. Fibrous feeds commonly contain high cellulose and hemicellulose concentrations that can create a complex with lignin to reduce the digestibility of the carbohydrates and discount efficient utilisation of roughage by ruminants. The poor nutrients and low digestibility are the hindrances in utilising straw as a feed. To take full advantage of straw and unlock its full nutritive potential, the lignin-cellulose structure must be broken and altered to increase accessibility to chemical and biological treatments. Generally, delignification methods fall into three fundamental categories: physical, chemical and biological treatments, the primary aim of which is to make carbohydrates and proteins more available to rumen microbes in ruminants (Severe and ZoBell, 2012).

Steam explosion, a promising biomass pre-treatment, adapted from pulp, paper, textile, chemical industries, could effectively cause lignin to be separated from polysaccharides (Kitani et al., 1989). Chang et al. (2012) reported that the cellulose, hemicellulose and lignin contents in corn straw could be decreased with steam explosion processing by 8.47, 50.45 and 36.65%, respectively. Viola et al. (2008) found that steam explosion increased the digestibility of wheat, barley, and oat straw by 25% in average. By now, steam explosion has been proved to be an effective way to improve biomass utilisation in industry production, while it is still a newly introduced technique in animal husbandry. In order to investigate the feasibility of applying it in ruminants feeding, this study was to determine the effect of steam explosion on \textit{in vitro} gas production (GP) and rumen fermentation profiles of the common straws, \textit{i.e.}, corn straw, wheat straw and rice straw.

Materials and methods

Fibrous feed samples and steam explosion process

Three individual samples of each of the fibrous feeds (corn straw, wheat straw and rice straw) were randomly collected before and after steam explosion processing. The condition parameters of steam explosion processing are as follows: container pressure, 2.0 Mpa; steam temperature, 200°C; heating time, 5 min; batch production, 2.5 ton. All the samples were dried at 60°C for 48 h in a forced air oven to constant weight, ground in a hammer mill to pass a 1 mm sieve and stored in sampling bags for subsequent determination of chemical components and \textit{in vitro} incubation.

\textit{In vitro} incubation procedure

\textit{In vitro} incubation was carried out according to the procedure of Menke et al. (1979). Rumen inoculum was collected from 3...
Simmental×Limousin cross-bred steers (approximately 450 kg body weight) fitted with permanent rumen cannula and fed twice a total mixed ration consisted of 50% hay and 50% concentrates before the morning feeding, strained through four layers of cheesecloth into a vacuum bottle and transported immediately to the laboratory of Beef Cattle Research Center of China Agricultural University. The rumen fluid was mixed with the buffer solution in a 1:2 (v/v) proportion under a continuous flux of CO₂. The buffer solution and rumen inoculum were prepared according to Menke and Steingass (1988). Samples of each feed were weighed (220 mg air dry matter) into 100 mL glass syringes and kept in 39°C incubator in advance. A total of 57 glass syringes (3 syringes of each triplicate sample for each of the six feeds with three syringes as blanks (i.e., rumen fluid only)), were incubated at 39°C for 96 h. The volume of GP was recorded manually at time-points of 0, 2, 4, 6, 8, 10, 12, 16, 20, 24, 30, 36, 42, 48, 54, 58, 60, 66, 72, 84 and 96 h of incubation. At the end of cultivation (i.e., 96 h), the fermentation mixture was measured for the final pH using a portable pH meter (Testo 265; Testo AG, Schwarzwald, Germany) and then centrifugated at 8000×g and 4°C for 15 min to obtain the non-fermented residues for the determination of dry matter degradability (DMD), meanwhile the supernatant was used to determine the concentrations of volatile fatty acids (VFA) and ammonia-nitrogen (NH₃-N) as well as cellulase activities. The non-fermented residues were dried at 105°C overnight to estimate DMD disappearance with loss in weight residues were dried at 105°C overnight to estimate DMD disappearance with loss in weight after drying. The VFA profile was determined as cellulase activities. The non-fermented residues were dried at 105°C overnight to estimate DMD disappearance with loss in weight after drying. The VFA profile was determined.

### Chemical analysis

Samples of the feeds were analysed for dry matter (DM), ash, and crude protein (CP) according to the AOAC (1997) procedures. The neutral detergent fibre (NDF), acid detergent fibre (ADF) and lignin (ADL) (AOAC, 1997) analysis used an A220 Fibre Analyzer (ANKOM Technology Corp., Macedon, NY, USA). NDF was assayed with use of an alpha amylase. Both NDF and ADF are expressed without residual ash.

### Calculations

To estimate kinetic parameters of GP, all the results of GP were fitted using the NLIN option of SAS version 9.0 according to France et al. (2000) as:

\[
A = b \times (1 - e^{-\beta(t-L)})
\]

where, \( A \) (mL/g DM) is the volume of GP at time \( t \), \( b \) (mL/g DM) is the asymptotic GP, \( c \) (h⁻¹) is the rate of gas production, and \( L \) (h) is the lag time prior to gas production.

### Statistical analysis

The experimental design for the in vitro rumen GP and fermentation parameters analysis was completely random 2×3 factorials design, considering type of straw (S) and steam explosion treatment (T) as fixed factors in the linear model. The data of three replicates within the same sample were averaged prior to statistical analysis. Mean values of each individual sample within each type (three samples of each) were used as the experimental unit. The statistical model was:

\[
Y_{ijk} = \mu + S_i + T_j + (S \times T)_{ij} + \epsilon_{ijk}
\]

where, \( Y_{ijk} \) is every observation of the \( i^{th} \) fibrous straw (S, type of straw) when processed by the \( j^{th} \) method (T, treatment); \( \mu \) is the general mean; \( S_i \) (i=1-3) is the straw effect; \( T_j \) is the treatment effect (j=1-2); \( (S \times T)_{ij} \) is the interaction type of straw and treatment;

### Table 1. Chemical compositions of raw straw and steam-exploded straw.

| Item        | Raw straw | Steam explosion | SEM | P    |
|-------------|-----------|-----------------|-----|------|
|             | Corn      | Wheat           | Rice|      |      |
| DM, %       | 92.88⁴    | 91.95⁵          | 93.20⁶| 93.96⁷| 94.95⁸| 94.65⁹| 0.06 | *** | *** | *** |
| Ash, %      | 7.03⁴     | 12.44⁵          | 12.65⁶| 9.50⁷ | 10.62⁸| 13.45⁹| 0.13 | *** | *** | *** |
| NDF, %      | 79.26⁴    | 73.48⁵          | 71.54⁶| 53.03⁷| 54.70⁸| 53.48⁹| 0.42 | *** | *** | *** |
| ADF, %      | 46.54⁴    | 45.93⁵          | 44.63⁶| 43.90⁷| 50.29⁸| 45.95⁹| 0.40 | *** | *** | *** |
| ADL, %      | 7.06⁴     | 7.81⁵           | 7.42⁶| 8.39⁷ | 10.34⁸| 8.62⁹| 0.41 | *** | *** | *   |
| CP, %       | 4.59⁴     | 5.07⁵           | 4.56⁶| 6.13⁷ | 4.19⁸ | 4.48⁹| 0.07 | *** | *** | *** |

5, type of straw; T, steam explosion treatment; S×T, interaction type of straw and steam explosion treatment; DM, dry matter; NDF, neutral detergent fibre; ADF, acid detergent fibre; ADL, acid detergent lignin; CP, crude protein. ⁴Different letters in the same row denote significant (P<0.05) differences among treatments. *P<0.05; **P<0.01; ***P<0.001.
e.g. is experimental random residual error. In order to examine the responses of different straw to the treatment, data were subjected to the GLM procedure of SAS (version 9.0; SAS Institute Inc., Cary, NC, USA), and Duncan’s test was used to determine the differences among the means with difference declared significant at P<0.05.

Results

Chemical compositions of raw straw and steam-exploded straw

The chemical compositions of the fibrous feeds before and after steam explosion processing are summarised in Table 1, mainly including the contents of DM, Ash, NDF, ADF, ADL and CP. In general, the chemical compositions varied (P<0.01) in different types of straw, meanwhile steam explosion processing had a significant effect (P<0.01) on the compositions, where the concentration of NDF decreased [ranging from 25.24% (rice straw) to 33.09% (corn straw)] and inverse for ADL [ranging from 18.84% (corn straw) to 32.63% (rice straw)]. Moreover, the interaction between the type of straw and steam explosion processing was significant (P<0.05).

In vitro gas production kinetics and cumulative gas production

Data concerning in vitro gas production kinetics and GP are presented in Table 2 and Figure 1. Both the type of straw and steam explosion processing significantly affected (P<0.01) the gas production parameters (b, c and L) and GP (except at 72 h and 96 h) along with notable interactions (P<0.01) except for b and GP at 96 h, being the rate of gas production (c) increased and the lag time (L) disappeared, while asymptotic gas production (b) decreased due to steam explosion processing and they showed difference in different type of straws.

Table 2. Gas kinetics and gas production of raw straw and steam-exploded straw fermented in in vitro rumen of beef cattle.

| Item | Corn | Wheat | Rice | Steam explosion | SEM | P |
|------|------|-------|------|-----------------|-----|---|
| GP parameters | | | | | | |
| b, mL/g | 225.8abc | 206.5bc | 233.7abc | 204.2bc | 191.3bc | 211.7bc | 2.4 | *** | *** | ns |
| c, h | 0.028abc | 0.032abc | 0.023abc | 0.049bc | 0.038bc | 0.043bc | 0.001 | *** | *** | *** |
| L, h | 1.697a | 2.120b | 0.903c | 0 | 0 | 0 | 0.130 | ** | *** | ** |
| GP, mL/g DM | | | | | | |
| GP1 | 20.5abc | 15.3abc | 24.4abc | 56.1abc | 45.3abc | 50.2abc | 1.5 | *** | *** | * |
| GP2 | 50.8abc | 50.2abc | 47.1abc | 94.4abc | 68.0abc | 82.8abc | 2.2 | *** | *** | *** |
| GP3 | 110.0abc | 109.3abc | 98.9abc | 141.4abc | 116.3abc | 130.2abc | 2.5 | *** | *** | *** |
| GP4 | 166.8abc | 159.2abc | 154.7abc | 182.1abc | 160.9abc | 183.6abc | 2.6 | *** | *** | *** |
| GP5 | 194.9abc | 181.9abc | 188.5abc | 193.2abc | 177.1abc | 202.4abc | 2.5 | *** | ns | ** |
| GP6 | 206.5abc | 194.6abc | 202.2abc | 204.2abc | 182.8abc | 207.2abc | 2.8 | *** | ns | ns |

S, type of straw; T, steam explosion treatment; S×T, interaction between type of straw and steam explosion treatment; b, asymptotic gas production; c, rate of gas production; L, initial delay before gas production begins; GP, gas production; DM, dry matter. “Different letters in the same row denote significant (P<0.05) differences among treatments. *P<0.05; **P<0.01; ***P<0.001; ns, not significant. *Zero value indicates that there is no lag time for the feed.

Table 3. Fermentation parameters of raw straw and steam-exploded straw after 96 h incubation in in vitro rumen of beef cattle.

| Item | Corn | Wheat | Rice | Steam explosion | SEM | P |
|------|------|-------|------|-----------------|-----|---|
| pH6.96abc | 6.96abc | 6.95abc | 6.93abc | 7.01abc | 6.91abc | 0.02 | * | ns | ns |
| NH3-N, mg/100 mL | 25.62abc | 36.10abc | 36.17abc | 32.73abc | 34.00abc | 34.01abc | 0.56 | ** | ns | ns |
| VFA, mmol/L | 41.59abc | 37.92abc | 38.80abc | 42.33abc | 42.41abc | 43.13abc | 0.65 | ns | ** | *** |
| Acetate, % | 66.23abc | 66.62abc | 66.12abc | 64.28abc | 63.44abc | 64.21abc | 0.13 | ns | ** | *** |
| Propionate, % | 19.25abc | 18.45abc | 18.95abc | 21.89abc | 22.86abc | 21.88abc | 0.06 | * | ** | *** |
| Isobutyrate, % | 1.12abc | 1.24abc | 1.30abc | 0.81abc | 0.89abc | 0.87abc | 0.05 | ** | * | *** |
| Butyrate, % | 9.32abc | 9.31abc | 9.22abc | 9.34abc | 8.97abc | 9.15abc | 0.04 | * | ** | *** |
| Isovalerate, % | 3.16abc | 3.45abc | 3.41abc | 2.90abc | 2.97abc | 3.01abc | 0.03 | *** | * | *** |
| Valerate, % | 0.93abc | 0.92abc | 0.99abc | 0.87abc | 0.87abc | 0.88abc | 0.01 | * | *** | ns |
| A/P | 3.44abc | 3.61abc | 3.49abc | 2.95abc | 2.78abc | 2.93abc | 0.01 | ns | *** | *** |
different types of straws. Steam explosion processing increased (P<0.01) total VFA production and the proportion of propionate (P), and decreased (P<0.01) the proportions of acetate, isobutyrate and valerate as well as the ratio A/P. Moreover, the interaction effect for VFA profile was significant (P<0.05) with an exception for valerate.

As to the cellulase activities, the type of straw had a significant effect (P<0.05) on the activities of avicelase and CMCase, and steam explosion processing significantly increased (P<0.01) all the cellulase activities with a significant interaction effect (P<0.01) for CMCase.

**In vitro rumen fermentation profile**

Data reflecting the rumen fermentation profile after 96 h incubation are summarised in Table 5, including ME, NEm, NEg, OMD, MCP, PF\textsubscript{96}, GY\textsubscript{24} and DMD. In general, the available energy concentrations (ME, NEm and NEg) and digestibilities (DMD and OMD) were different (P<0.01) between different types of straws, and steam explosion processing increased (P<0.05) their available energy concentrations and digestibilities. Moreover, the interaction effect was significant (P<0.01) for ME, NEm, NEg and OMD. The type of straw and steam explosion processing exerted no effect (P>0.05) on MCP, PF\textsubscript{96} and GY\textsubscript{24}.

**Discussion**

**Effect of steam explosion on the chemical compositions of fibrous straw**

The chemical contents of the three feeds in the present study were comparable with those reported previously (Sarkar et al., 2012), and differences in the compositions between the fibrous feeds were notable. Practically, untreated mature straw is high in lignification and tight to digest, resulting in a low digestibility and poor nutritive value. Processing treatment is essentially undertaken to bring about a change in the structure of biomass as well as the chemical compositions (Sarkar et al., 2012). Steam explosion is a promising pretreatment method, which makes biomass more accessible to cellulase attack (Neves et al., 2007). Currently, steam explosion processing made a significant change in chemical compositions of the feeds, being that the content of NDF decreased and converse for ADL. The results almost agreed with Chang et al. (2012) reporting that steam explosion treatment could decrease the content of cellu-
lose and hemicellulose in corn straw. It may be explained as steam explosion broke the lignocellulosic complex, depolymerising the matrix of cellulose, hemicellulose and lignin and unlocking the intracellular nutrients. Consistently, Kitani et al. (1989) reported that steam explosion effectively caused lignin to be separated from polysaccharides. When steam is allowed to expand within the lignocellulosic matrix, it separates the individual fibres (Sarkar et al., 2012). What’s more, the significant changes in NDF and ADL but not ADF suggested that hemicellulose was largely released due to steam explosion processing. The different interactions straw type×treatments inferred that straws with different structures and constituents showed different responses to steam explosion processing, consequently resulting in different fermentation profiles. Additionally, the relative change of each component and the recovery rate of steam explosion processing should partly account for the changes of chemical compositions.

**Effect of steam explosion on in vitro rumen fermentation parameters of fibrous straw**

In general, GP appeared to be related to the chemical compositions of the feed, in particular to the fibre content, being that more fermentable substrate would produce larger GP. Wang and Zhang (2013) reported that steam explosion could increase the biogas production of cornstalk by 16.8–63.2%. Increased in vitro GP may allow higher voluntary feed intake (Gado et al., 2009) by decreasing physical rumen fill, increasing the energy density of the diets and stimulating MCP production (Oba and Allen, 2000). Compared to the raw straw, larger GP for the steam-exploded straw was in consistent with the components changes (NDF decreased), suggesting that steam explosion processing could improve the nutritive values of the fibrous feeds. Several studies have shown that steam explosion processing could increase the digestion of fibrous feeds measured in vitro (Van Soest, 2006; Viola et al., 2008). Moreover, steam explosion also induced a faster fermentation as the lag time disappeared and the GP rate was higher. This effect could be due to the changes in fibre structures and compositions. Steam explosion depolymerised the lignocellulosic structure to free the cellulose and hemicellulose and unlocked the intracellular nutrients, providing more fermentable substrates to stimulate microbial growth (Forsberg et al., 2000) and larger surface for microbial attachment, consequently secreting more digestive enzymes and maintaining a more efficient fermentation. In addition, hydrolysis of hemicellulose and some other components during processing would produce amounts of readily fermentable sugars such as glucose, xylose, arabinose, etc.

In the present study, steam explosion processing was also effective in improving in vitro VFA profile, NH₃-N concentration and cellulase activities. As is well known, VFA is the major source of energy supply for ruminants. Larger VFA production verified that steam explosion could increase the energy concentration of the feeds, which agreed with the inference by GP aforementioned. Furthermore, a decrease in the ratio between acetate and propionate was expected in the current in vitro fermentation, and the shift towards propionate fermentation might be explained by a decreased energy loss as methane during rumen fermentation (Zinn et al., 2002), inferring that steam explosion could improve the efficiency of energy utilisation. Consistently, it has been shown that steam explosion-treated rice straw had higher gas production and VFA concentration, suggesting that steam explosion treatment may be used to enhance the nutritive value and digestibility of the rice straw. Regrettably, there existed no literature about the influence

### Table 4. Cellulase activities of raw straw and steam-exploded straw after 96 h incubation in in vitro rumen of beef cattle.

| Enzyme activity, mU | Raw straw | Steam explosion | SEM       | P     |
|---------------------|-----------|-----------------|-----------|-------|
|                     | Corn      | Wheat           | Rice      |       |
| Avicelase           | 308.01ab  | 327.44ab        | 300.52a   |       |
|                     | 341.44ab  | 392.78b         | 345.69b   | 13.24 |
| CMCase              | 172.66    | 167.37a         | 166.09a   |       |
|                     | 197.84b   | 216.13b         | 211.19c   | 2.33  |
| β-glucanase         | 336.52ab  | 317.99a         | 322.04a   |       |
|                     | 373.79bc  | 415.60b         | 373.01bc  | 13.77 |
| Xylanase            | 109.77a   | 116.59ab        | 122.24bc  |       |
|                     | 128.53bc  | 139.90b         | 127.75bc  | 5.81  |

S, type of straw; T, steam explosion treatment; S×T, interaction between type of straw and steam explosion treatment; CMC, carboxymethyl cellulase. *P<0.05; **P<0.01; ***P<0.001; ns, not significant. ‘Different letters in the same row denote significant (P<0.05) differences among treatments.

### Table 5. Fermentation profiles of raw straw and steam-exploded straw after 96 h incubation in in vitro rumen of beef cattle.

| Item           | Raw straw | Steam explosion | SEM       | P     |
|----------------|-----------|-----------------|-----------|-------|
|                 | Corn      | Wheat           | Rice      |       |
| ME, MJ/kg       | 6.05b     | 6.19b           | 5.74b     | 7.46b |
|                 | 6.10b     | 6.78b           | 6.78b     | 0.06  |
| NEEm, MJ/kg     | 4.44a     | 4.56a           | 4.18a     | 5.78a |
|                 | 4.48b     | 5.10b           | 5.10b     | 0.05  |
| NEg, MJ/kg      | 3.27b     | 3.37b           | 3.08b     | 4.33b |
|                 | 3.30b     | 3.78b           | 3.78b     | 0.04  |
| DMD, g/kg       | 523.18b   | 370.54a         | 407.15b   | 536.60a |
|                 | 430.53bc  | 531.46a         | 32.45     |
| OMD, g/kg       | 410.69b   | 446.87b         | 427.54c   | 489.57d |
|                 | 445.43b   | 502.17b         | 4.62      |
| MCP, g/kg       | 281.30    | 150.23          | 189.58    | 225.48 |
|                 | 174.74    | 227.48          | 24.07     |
| PFe₄, mg/mL     | 4.78      | 3.40            | 4.15      | 3.80  |
|                 | 3.71      | 3.85            | 0.30      |
| GY₂₄, mL/Lq     | 211.32    | 297.57          | 244.51    | 260.57 |
|                 | 20.39     | 277.15          | 267.27    |

S, type of straw; T, steam explosion treatment; S×T, interaction between type of straw and steam explosion treatment; ME, metabolisable energy; NEEm, net energy for maintenance; NEg, net energy for growth; DMD, dry matter digestibility; OMD, organic matter digestibility; MCP, microbial crude protein; PF₉₆, partitioning factor at 96 h of incubation; GY₂₄, gas yield after 24 h of incubation. *P<0.05; **P<0.01; ***P<0.001; ns, not significant. ‘Different letters in the same row denote significant (P<0.05) differences among treatments.

*Ital J Anim Sci vol.14:2015*
of steam explosion processing on fermentation parameter NH3-N. Decrease in NH3-N concentration could be due to protein content changes and its bioavailability cut down because of Maillard reaction during steam explosion processing, or more NH3-N used in MCP production by rumen microorganisms. As to enzyme activity, the increased cellulase activities supported it that the microbial activity involving in fibre digestion was improved due to steam explosion processing, in line with the changes of GP and VFA aforementioned. It could be partly expressed as treated straws provided more nutrients and substrate for microbial growth. Yu et al. (1998) noted that high amylase activities in the intestinal contents reflected a large amount of starch available for microbial growth, while the activities of cellulases indicated active populations of cellulolytic bacteria. With the increase of VFA and decrease of NH3-N, the final pH would be expected to decline when compared to raw straws.

**Effect of steam explosion on in vitro rumen fermentation profile of fibrous straw**

Typically, the in vitro GP at 24 h of ruminant feeds is highly correlated with their digestibilities and available energetic contents (Menke et al., 1979). Moreover, the energy content of feedstuff is highly correlated with their digestibility of DM or OM (Rittenhouse et al., 1971; Van and Agnew, 2004). Several studies have shown that steam explosion processing could increase the digestibility of fibrous feeds measured in vitro (Van Soest, 2006; Viola et al., 2008). Consistently, the present results showed that steam explosion processing increased the digestibilities (DMD and OMD) and energy concentrations (ME and NE) of the fibrous feeds. As steam explosion processing loosened the fibre structure and increased the saccharide content by depolymerising the cell wall (Wang et al., 2009), these improvements may have contributed to the increased fibre digestion and altered rumen fermentation (Nsereko et al., 2002), enhanced attachment and colonisation to the plant cell wall material by rumen microorganisms (Wang et al., 2001). Corresponding to the digestibility, the energy value predicted by GP and CP was increased. However, there was no difference on the fermentation efficiency (PF96 and GY24), which could be explained as both DMD and GP increased and their ratio hardly changed.

**Conclusions**

Different types of straw had various chemical compositions, which were significantly influenced by steam explosion processing, consequently resulting in the remarkable differences on the in vitro rumen fermentation profiles of steam-exploded straw and raw straw. The collective findings of the present study suggest that steam explosion processing of fibrous feeds could improve their rumen fermentability and energy utilisation by ruminants, and utilisation of steam explosion in animal feeding would be practical.

**References**

AOAC, 1997. Official methods of analysis. 16th ed. Association of Official Analytical Chemists, Arlington, VA, USA.

Asseng, S., Foster, I., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Global Change Biol. 17:997-1012.

Blümml, M., Steinga, H., Becker, K., 1997. The relationship between in vitro gas production, in vitro microbial biomass yield and N incorporation and its implications for the prediction of voluntary feed intake of roughages. Brit. J. Nutr. 77:311-321.

Broderick, G.A., Kang, J.H., 1980. Automated simultaneous determination of ammonia and total amino acids in ruminal fluid and in vitro media. J. Dairy Sci. 63:64-75.

Chang, J., Yin, Q.Q., Ren, T.B., Song, A.D., Zuo, R.Y., Guo, H.W., 2012. Effect of steam explosion pretreatment and microbial fermentation on degradation of corn straw. Adv. Mat. Res. 343:809-814.

Erwin, E.S., Marco, G.J., Emery, E.M., 1961. Volatile fatty acid analyses of blood and rumen fluid by gas chromatography. J. Dairy Sci. 44:1768-1771.

Forsberg, C.W., Forano, E., Chesson, A., 2000. Microbial adherence to the plant cell wall and enzymatic hydrolysis. Ruminant physiology digestion, metabolism, growth and reproduction. CABl Publ, Wallingford, UK.

France, J., Dijkstra, J., Dhanoa, M.S., Lopez, S., Bannink, A., 2000. 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. Brit. J. Nutr. 83:143-150.

Gado, H.M., Salem, A., Robinson, P.H., Hassan, M., 2009. Influence of exogenous enzymes on nutrient digestibility, extent of ruminal fermentation as well as milk production and composition in dairy cows. Anim. Feed Sci. Tech. 154:36-46.

Karimi, K., Kheradmandinia, S., Taherzadeh, M.J., 2006. Conversion of rice straw to sugars by dilute-acid hydrolysis. Biomass. Bioenerg. 30:247-253.

Kitani, O., Hall, C.W., Wagener, K., 1989. Biomass. Handbook. Gordon & Breach, New York, NY, USA.

Liu, Q., Wang, C., Pei, C.X., Li, H.Y., Wang, Y.X., Zhang, S.L., Zhang, Y.L., He, J.P., Wang, H., Yang, W.Z., Bai, Y.S., Shi, Z.G., Liu, X.N., 2014. Effects of isovalerate supplementation on microbial status and rumen enzyme profile in steers fed on corn stover based diet. Livest. Sci. 161:60-68.

Males, J.R., 1987. Optimizing the utilization of cereal crop residues for beef cattle. J. Anim. Sci. 65:1124.

Menke, K.H., Raab, L., Salewski, A., Steingass, H., Fritz, D., Schneider, W., 1979. The estimation of the digestibility and metabolizable energy content of ruminant feedstuffs from the gas production when they are incubated with rumen liquor in vitro. J. Agr. Sci. 93:217-222.

Menke, K.H., Steingass, H., 1988. Estimation of the energetic feed value obtained from chemical analysis and in vitro gas production using rumen fluid. Anim. Res. Dev. 28:7-55.

National Research Council, 2000. Nutrient requirements of beef cattle. 7th rev. ed. National Academy Press, Washington, DC, USA.

Neves, M.A., Kimura, T., Shimizu, N., Nakajima, M., 2007. State of the art and future trends of bioethanol production, dynamic biochemistry, process biotechnology and molecular biology. Dyn. Biochem. Process Biotechnol. Mol. Biol. 1:1-14.

Nsereko, V.L., Beauchemin, K.A., Morgavi, D.P., McAllister, T.A., Iwasa, A.D., Yang, W.Z., Wang, Y., 2002. Effect of a fibrolytic enzyme preparation from Trichoderma longibrachiatum on the rumen microbial population of dairy cows. Can. J. Microbiol. 48:14-20.

Oba, M., Allen, M.S., 2000. Effects of brown midrib 3 mutation in corn silage on productivity of dairy cows fed two concentrations of dietary neutral detergent fibre: 3. Digestibility and microbial efficiency. J. Dairy Sci. 83:1350-1358.

Rittenhouse, L.R., Streeter, C.L., Clanton, D.C., 1971. Estimating digestible energy from digestible dry and organic matter in diets of grazing cattle. J. Range Manage. 24:73-75.

[page 732] [Ital J Anim Sci vol.14:2015]
Sarkar, N., Ghosh, S.K., Bannerjee, S., Aikat, K., 2012. Bioethanol production from agricultural wastes: an overview. Renew. Energ. 37:19-27.
Severe, J., ZoBell, D.R., 2012. Review. Technical aspects for the utilization of small grain straws as feed energy sources for ruminants: emphasis on beef cattle. Available from: http://extension.usu.edu/htm/publications/publication=14534&custom=1
Van Soest, P.J., 2006. Rice straw, the role of silica and treatments to improve quality. Anim. Feed Sci. Tech. 130:137-171.
Viola, E., Zimbardi, F., Cardinale, M., Cardinale, G., Braccio, G., Gambacorta, E., 2008. Processing cereal straws by steam explosion in a pilot plant to enhance digestibility in ruminants. Bioresource Technol. 99:681-689.
Wang, K., Jiang, J., Xu, F., Sun, R., 2009. Influence of steaming explosion time on the physic-chemical properties of cellulose from Lespedeza stalks (Lespedeza cryptobotrya). Bioresource Tech. 100:5288-5294.
Wang, X.T., Zhang, B.L., 2013. Study on anaerobic digestion of steam-explosion pretreated cornstalk. China Biogas 31:10-14.
Wang, Y., McAllister, T.A., Rode, L.M., Beauchemin, K.A., Morgavi, D.P., Nsereko, V.L., Iwaasa, A.D., Yang, W., 2001. Effects of an exogenous enzyme preparation on microbial protein synthesis, enzyme activity and attachment to feed in the Rumen Simulation Technique (Rusitec). Brit. J. Nutr. 85:325-332.
Yan, T., Agnew, R.E., 2004. Prediction of metabolisable energy concentrations from nutrient digestibility and chemical composition in grass silages offered to sheep at maintenance. Anim. Feed Sci. Tech. 117:197-213.
Yu, B., Tsai, C.C., Hsu, J.C., Chiou, P.W., 1998. Effect of different sources of dietary fibre on growth performance, intestinal morphology and caecal carbohydrates of domestic geese. Brit. Poultry Sci. 39:560-567.
Zeng, X., Ma, Y., Ma, L., 2007. Utilization of straw in biomass energy in China. Renew. Sust. Energ. Rev. 11:976-987.
Zinn, R.A., Owens, F.N., Ware, R.A., 2002. Flaking corn: processing mechanics, quality standards, and impacts on energy availability and performance of feedlot cattle. J. Anim. Sci. 80:1145-1156.