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Effect of saponins and plant extracts containing saponins on the recovery of ammonia during urea-ammoniation of wheat straw and fermentation kinetics of the treated straw

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SUMMARY

Saponins of *Quillaja saponaria* bark and the water extract obtained on homogenization of *Yucca schidigera* plants were used during urea-ammoniation to reduce ammonia loss. In Expt 1, chaffed wheat straw (2–5 cm length) was urea-ammoniated (50 g kg^{-1} urea, 400 g kg^{-1} moisture) for 25 days at 37 °C with and without *Quillaja* saponins (QS) or *Yucca* plant homogenate, YPH (corresponding to 1 and 2 g kg^{-1} *Yucca* powder). The crude protein (CP) content of untreated straw was 34 g kg^{-1}. After 25 days, CP values of 90 g kg^{-1} (urea; no saponin), 82 and 86 g kg^{-1} (urea + QS at 1 and 2 g kg^{-1}) and 102 and 92 g kg^{-1} (urea + YPH at 1 and 2 g kg^{-1}) were obtained. The ammonia-nitrogen bound (as percentage of urea-nitrogen added) to straw after the treatment was 39 (urea; no saponin), 33 and 36 (urea + QS at 1 and 0·2 g kg^{-1}), and 47 and 40 (urea + YPE at 1 and 2 g kg^{-1}). As the extent of ammonia bound to straw was higher with *Yucca* plant powder, especially at 1 g kg^{-1}, *Yucca* plant powder at 0·75 and 1 g kg^{-1} was used in Expt 2. In Expt 1, the *Yucca* plant extract was used after homogenization of the *Yucca* plant powder, which is not feasible at farm level. Therefore, two simpler approaches (overnight soaking of the powder in water (*Yucca* powder extracted, YPE) and mixing of *Yucca* powder with the straw followed by urea-ammoniation (*Yucca* powder, YP) were used besides homogenization. Otherwise, conditions for the urea-ammoniation treatment were similar to those in Expt 1. The ammonia–nitrogen bound (as percentage of urea-nitrogen added) to the straw varied from 47 to 54% in the presence of the *Yucca* plant powder, which was substantially higher than that observed in its absence (38%). The ammonia-binding efficiency of *Yucca* plant powder to the straw was highest at 1 g kg^{-1}. Among the three methods tried, addition of the *Yucca* powder to straw followed by treatment with urea was the easiest, and the binding efficiency was similar to that observed when using the powder after homogenization. In both experiments, the true dry matter- and NDF-digestibilities, calculated organic matter digestibility and metabolizable energy, as well as rate and potential extent of gas production, were significantly higher ($P < 0·05$) in the treated straw than in the untreated straw. These values were affected neither by the source of the saponins nor the manner in which the *Yucca* powder was applied.

INTRODUCTION

In many parts of the world, poor quality hays, pastures and crop residues form a major part of the feed resources for ruminants. Protein deficiency and low digestibility often restrict animal performance (Klopfenstein *et al*. 1991; McAllan 1991). Attempts to improve intake and utilization of poor quality roughages have included physical processing, chemical treatment or a combination of both (Jackson 1977; Sundstøl *et al*. 1979; Sharma *et al*. 1993).

Extensive information exists on the treatment of straw using ammonia released by the hydrolysis of urea (Jayasuriya & Pearce 1983; Makkar & Singh 1987). Compared with chemicals such as sodium hydroxide or ammonia, urea is cheaper, non-corrosive

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and available in most developing countries, and this favours its use in improving the nutritive value of low quality straw. Other beneficial effects of this indirect method of ammoniation of straw have been discussed by Davies (1983). However, a major drawback of this process is the loss of nitrogen (N) in the form of ammonia after upgrading is completed.

Saponins are secondary metabolites of plants (Johnson *et al*. 1986) which occur in numerous forages and crops consumed by livestock. They are defined as high-molecular-weight glycosides, consisting of a sugar moiety linked to a triterpene or steroid aglycone (Hostettmann & Marston 1995). *Yucca* and *Quillaja* extracts have been used as feed additives, especially for monogastrics, to control ammonia in stables. This has resulted in improved animal performance (Rowland *et al*. 1976; Johnston *et al*. 1981). Saponins and glyco components present in these extracts are thought to trap ammonia (Hussain *et al*. 1996). In this study, saponins and saponin-containing plant extracts were used during urea-ammoniation to reduce ammonia loss to the air. The recovery of ammonia during urea-ammoniation of wheat straw in the presence and absence of *Quillaja saponaria* bark saponins and *Yucca schidigera* plant extract (the saponins from these sources have been classified as 'generally recognised as safe' for permitted food use in the USA), as well as the fermentation kinetics of the treated straw, were investigated.

MATERIALS AND METHODS

Experiment 1: Treatment with Quillaja saponaria *bark saponins and* Yucca schidigera *plant extract*

Wheat straw, chaffed to 2–5 cm, containing 100 g kg^{-1} moisture was used for the experiment.

Treatment using Quillaja *saponins*

Urea (5 g) and 100 or 200 mg of *Quillaja* bark saponins (*Quillaja* saponin S–2149 Lot 73H2605; Sigma Chemical Co, St. Louis, Missouri) were mixed in 50 ml distilled water (saponins are 100% soluble) and sprayed over 100 g of the straw. These treatments were designated QS_1 [1 g kg^{-1} *Quillaja* bark saponin + 50 g kg^{-1} urea] and QS_2 [2 g kg^{-1} *Quillaja* bark saponin + 50 g kg^{-1} urea].

Treatment using Yucca *extract*

Y. schidigera plant extract (300 and 600 mg) available commercially as a powder (DK Sarsaponin 3; Desert King International, Chula Vista, USA) was homogenized in 150 ml distilled water using an Ultra-Turrax homogenizer (20000 rpm) and for 8 min (4 × 2 min). The homogenized contents were transferred into plastic bottles and centrifuged at 4000 ***g*** for 10 min. The residue was discarded. The supernatant (50 ml) was mixed with 5 g urea and added to 100 g straw. This treatment was designated '*Yucca* powder homogenized' YPH; YPH_1 (water extract corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea) and YPH_2 (water extract corresponding to 2 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea).

The straw was thoroughly mixed to ensure uniform wetting and packed into plastic bottles. Moisture was 40% during urea treatment. The air present in the bottles was removed with a vacuum pump. While the vacuum pump was on, the bottles were screw-capped and sealed immediately using parafilm 'M' Laboratory film (American National Can, Neenah, WI) to ensure airtight conditions. The sealed plastic bottles were stored at 37 °C. The bottles were opened after 25 days and the straw was aerated for 2 days by spreading it on laboratory trays kept at *c*. 22 °C under a hood. The samples were dried and ground with a mill to pass through a 1 mm sieve. A control (C), that had urea but no saponins was subjected to storage and drying treatments similar to the treated samples. Each treatment was carried out in duplicate. The untreated straw was designated Un.

Experiment 2: Treatment with Y. schidigera *plant extract added in different forms*

Wheat straw (chaffed 2–5 cm in length, 100 g kg^{-1} moisture) from a batch different from that used in Expt 1 was treated. Moisture and urea were adjusted to 400 g kg^{-1} and 50 g kg^{-1} respectively, as above. The batch and commercial source of *Y. schidigera* plants were the same as in Expt 1. The *Yucca* powder was used in three different ways.

In treatment 1, the *Y. schidigera* powder (225 and 300 mg) was homogenized in 150 ml of distilled water using an Ultra-Turrax (20000 rpm) for 8 min (4 × 2 min). The homogenized contents were transferred into plastic bottles and centrifuged at 4000 ***g*** for 10 min. The residue was discarded. The supernatant (50 ml) was mixed with 5 g urea and added to 10 g straw. This treatment was designated '*Yucca* powder homogenized', YPH, YPH_3 (extract corresponding to 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea) and YPH_4 (extract corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea).

In treatment 2, the *Y. schidigera* powder (75 and 100 mg) was mixed with 50 ml of distilled water in a beaker, covered and kept overnight at room temperature. Urea (5 g) was added to the beaker on the following day and the contents mixed thoroughly using a glass rod. The contents, while being stirred, were added to 100 g of the straw. This treatment was designated '*Yucca* powder extracted', YPE; YPE_1 (extract corresponding to 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea) and YPE_2

(extract corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea).

In treatment 3, the *Y. schidigera* powder (75 and 100 mg) was mixed thoroughly with 100 g of straw. Later 5 g of urea dissolved in 50 ml distilled water was added to the straw and mixed uniformly. This treatment was designated '*Yucca* powder', YP; YP_1 (0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea) and YP_2 (1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea).

Two control treatments were maintained: (1) with urea but no saponin, C_1, and (2) saponin extract (prepared as in treatment 2) at 0·75 and 1 g kg^{-1} but no urea; designated C_{2a} and C_{2b}, respectively. Each treatment was carried out in duplicate in polyethylene bags. The bags were filled with the treated straw, squeezed to expel air and the remaining air was then removed using a vacuum pump. The bags were tied to ensure airtight conditions and then stored at 37 °C. The bags were opened after 25 days and the straw was processed as in Expt 1.

Nutritional evaluation using an in vitro *gas method*

Samples (200 mg) were weighed into 100 ml calibrated syringes and inoculated with a buffered medium containing rumen fluid (Menke & Steingass 1988). Parallel incubations for measurement of gas production without substrate (blank) or with 200 mg of hay reference standard were also carried out. Incubations were stopped at 24 h. Using crude protein (CP), ash (A) and net gas production at 24 h, Gv (after correcting for the blank and the gas released from the standard), organic matter digestibility (OMD, %) and metabolizable energy (ME, MJ kg^{-1} DM) were calculated using the following equations proposed by Menke & Steingass (1988).

$$OMD = 14{\cdot}88 + 0{\cdot}889*Gv + 0{\cdot}45*CP + 0{\cdot}65*A$$

and

$$ME = 2{\cdot}20 + 0{\cdot}136*Gv + 0{\cdot}057*CP$$

In these equations, Gv is in ml and CP and A are percentages.

True digestibility

For determination of true digestibility, 500 mg of samples were incubated with 40 ml buffered medium containing rumen fluid (Makkar *et al.* 1995). True digestibility was determined after 24 h incubation by treating the syringe contents with the neutral detergent solution to obtain neutral detergent fibre (NDF). Truly digested substrate was the difference in weight between the sample taken for incubation and the NDF residues (Makkar *et al.* 1995).

Rate and potential extent of gas production

The samples (200 mg) were incubated in triplicate in graduated syringes containing 30 ml of the *in vitro* medium containing rumen liquor (Menke & Steingass 1988). At 2, 4, 6, 8, 10, 12, 24, 30, 36, 48, 54, 60, 72 and 96 h, gas values were recorded. The potential extent (b) and rate (c) of gas production were determined using a one pool exponential model, $y = b(1-e^{-ct})$, where y is the gas produced (ml) at time t (h).

Other analyses

Proximate components were analysed according to AOAC (1980) methods. Fibre analyses (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) were determined by the procedures of Van Soest *et al.* (1991). Urea in the straw samples was determined as described by Makkar & Singh (1987).

Statistical analysis

The significant of differences between means was compared using the Least Significant Difference test after ANOVA for one-way classified data with the aid of the SAS/STAT program (SAS 1988). $P < 0{\cdot}05$ was chosen as the minimum probability value for statistical significance.

RESULTS AND DISCUSSION

Experiment 1

Data on the chemical composition of untreated and treated straw are presented in Table 1. The straw treated with QS had lower CP than the control (urea but no saponin). The recovery of urea-N as ammonia-N bound to the straw after treatment was 39 (C), 33 and 36 (QS_1 and QS_2), and 47 and 40 % (YPH_1 and YPH_2). Urea was not detected in any of the treated samples. During incubation, urea is converted to ammonia by urease from contaminant microbes present in the straw (Makkar & Singh 1987). Therefore, the bound N is in the form of ammonia. The *Yucca* plant extract increased the amount of ammonia-N in the straw compared with the control. On the other hand, *Quillaja* bark saponins had a negative effect. The differences observed between the two saponins could be due to structural differences (*Yucca* saponins are steroidal while *Quillaja* saponins are triterpenoidal in nature) or to the presence of some components other than saponins in the *Yucca* extract which have high affinity with ammonia. It may be noted that *Yucca* plant extract contains many other moieties besides saponins, whereas *Quillaja* saponins used were from Sigma which may be considered to be a preparation comprising mainly of a group of saponins from *Quillaja* bark. The presence of a glycoprotein in *Yucca* preparations having a high affinity for ammonia has been reported (Headon *et al.* 1991). Milgate & Roberts (1995) observed that small structural differences in saponins can cause considerable variation in their ammonia-binding

Table 1. *Chemical composition and ammonia–nitrogen bound to straw treated with urea in the presence and absence of saponins or saponin-containing extract*

	Un	C	QS_1	QS_2	YPH_1	YPH_2	S.E. (D.F. for error = 5)
Chemical composition (g kg^{-1} in DM)							
Crude protein	34	90	82	86	102	92	1·1
Ash	89	73	77	76	62	83	1·8
NDF	755	743	755	747	741	743	8·3
ADF	604	622	616	612	612	622	8·6
ADL	107	123	117	112	113	118	6·1
Ammonia– nitrogen bound to straw (% of urea-nitrogen added*)	—	39·2	33	37·4	46·7	39·9	1·3

C, control; Un, untreated; QS_1, 1 g kg^{-1} *Quillaja* bark saponin + 50 g kg^{-1} urea; QS_2, 2 g kg^{-1} *Quillaja* bark saponin + 50 g kg^{-1} urea; YPH_1, water extract (after homogenization) corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPH_2, water extract (after homogenization) corresponding to 2 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea.
* Urea-nitrogen added for urea-ammoniation (expressed on DM basis): 23·3 g kg^{-1} straw.
NDF, neutral detergent fibre; ADF, acid detergent fibre; ADL, acid detergent lignin.

Table 2. *Effect of saponins or saponin-containing extracts on net gas production, mg substrate truly digested/ml gas produced, true dry matter-, neutral detergent fibre (NDF)- and organic matter (OM)-digestibility and metabolizable energy (ME) of straw, and on the rate* (c) *and potential extent* (b) *of gas production from straw*

	Treatments						
	Un	C	QS_1	QS_2	YPH_1	YPH_2	S.E. (D.F. for error = 5)
Net gas produced (200 mg/24/h)	21·9	27·8	27·6	25·6	27·2	26·9	0·62
Substrate truly digested (mg)/ml gas produced	3·8	3·7	3·6	3·5	3·7	3·6	0·11
True DM digestibility (%)	42·1	52·1	51·4	50·6	51·1	52·3	0·91
NDF digestibility (%)	28·9	39·9	39·9	38·4	38·6	40·4	1·28
OM digestibility (%)	33·8	43·7	43·1	41·6	43·7	42·9	1·03
ME (MJ/kg DM)	5·3	6·5	6·4	6·2	6·5	6·4	0·19
Rate *c* (h^{-1})	0·0298	0·0361	0·035	0·0323	0·0338	0·0335	0·0005
Potential *b* (ml)/200 mg	38·9	48·0	48·1	47·8	47·3	47·2	0·81

C, control; Un, untreated; QS_1, 1 g kg^{-1} *Quillaja* bark saponin + 50 g kg^{-1} urea; QS_2, 2 g kg^{-1} *Quillaja* bark saponin + 50 g kg^{-1} urea; YPH_1, water extract (after homogenization) corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPH_2, water extract (after homogenization) corresponding to 2 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea.

capacity. Degradation of *Quillaja* saponins during the anaerobic conditions of the treatment can not be ruled out (Makkar & Becker 1997).

The true DM-, NDF- and organic matter digestibilities, ME and rate potential extent of gas production were significantly higher ($P < 0·05$) in the treated than in the untreated straw (Table 2). A substantial increase in these values was observed after urea-ammoniation, although the values were similar for the straw treated in the presence or absence of saponins or saponin-containing plant extracts. The results suggest that the fermentation kinetics of urea-treated straw in the presence or absence of saponins were similar. The only advantage of saponin addition was the higher retention of ammonia in the straw. The YPH was better than QS in trapping ammonia.

As maximum binding of ammonia-nitrogen was observed in the presence of YPH at a content of 1 g kg^{-1}, the 0·75 and 1 g kg^{-1} treatments of *Yucca* plant powder were selected for a further experiment.

Table 3. *Chemical composition and percentage of ammonia–nitrogen bound to straw treated with urea in the presence and absence of* Yucca schidigera *plant extracts*

	Un	C_1	C_{2a}	C_{2b}	YPH_3	YPH_4	YPE_1	YPE_2	YP_1	YP_2	S.E. (D.E. for error = 9)
Chemical composition (g kg^{-1} in DM)											
Crude protein	28	83	27	28	102	105	96	100	98	104	2·4
Ash	83	77	81	89	95	88	79	68	91	72	2·3
NDF	748	731	759	761	726	721	724	733	718	751	10·0
ADF	661	666	685	686	655	648	664	667	649	670	8·4
ADL	106	107	108	110	102	104	106	104	104	107	4·6
Ammonia–nitrogen bound to straw (% of urea-nitrogen added*)	—	37·8	—	—	50·8	52·90	46·5	49·4	48·1	52·2	1·9

Un, untreated; C_1 with urea but no saponin; C_{2a} and C_{2b}, saponin extract at 0·75 and 1 g kg^{-1} respectively but no urea; YPH_3, extract (after homogenization) corresponding to 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPH_4, extract (after homogenization) corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPE_1, extract (without homogenization) corresponding to 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPE_2, extract (without homogenization) corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YP_1, 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YP_2, 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea.

* Urea-nitrogen added for urea-ammoniation (expressed on DM basis): 23·3 g kg^{-1} straw.

NDF, neutral detergent fibre; ADF, acid detergent fibre; ADL, acid detergent lignin.

In Expt 1, the *Yucca* plant extract was used after homogenization of the *Yucca* plant powder, but this is not feasible under practical conditions. Therefore, the *Yucca* plant powder was used in two other ways (see Materials and Methods) which are simpler. The efficiency of these treatments was compared with that observed when the extract was prepared by homogenization of the *Yucca* plant powder.

Experiment 2

Table 3 presents data on chemical composition of untreated and treated straw. The straw treated with YPH_3 and YPH_4 but no urea (C_{2a} and C_{2b}) had the same CP content as the untreated straw, suggesting no contribution of N from the *Yucca* plant extract. The CP contents of the straw treated with urea in presence of the *Yucca* plant extracts (9·6–10·5 %) were higher than in its absence (C_1; 8·3 %). The ammonia bound (percentage of urea-nitrogen added) to the straw varied from 47 to 54 % in the presence of the *Yucca* plant powder, which was substantially higher than that observed in its absence (38 %). The efficiency of the *Yucca* plant powder in binding ammonia-nitrogen was higher at 1 than at 0·75 g kg^{-1}. From the three methods tested, the addition of *Yucca* powder to the straw followed by treatment with urea was the easiest, and the binding efficiency of ammonia-nitrogen by this treatment at 1 g kg^{-1} of the powder was similar to that observed when using the extract prepared after homogenization of the *Yucca* powder.

The OMD, true dry matter- and NDF-digestibilities, ME and rate and potential extent of gas production were significantly higher ($P < 0·05$) in the treated than in the untreated straw (Table 4). These values were not affected by the manner in which the *Yucca* powder was prepared. The differences observed in the digestion characteristics of the treated straw samples from Expts 1 and 2 appear to be due to the different batches of straw used.

The inoculation of urea-ammoniated straw with a lignocellulolytic fungus (*Coprinus fimetarius*) has been used to trap ammonia. This fungus is capable of growing under high pH conditions and converts urea/ammonia-nitrogen into fungal nitrogen, thereby reducing the loss of ammonia to the air (Walli *et al.* 1993). These authors reported a reduction in soluble nitrogen and NH_3-nitrogen (as % of total nitrogen) from 68 and 48 % to 27 and 4 % respectively, on day 7 of fungal growth. In comparison to the present approach of trapping ammonia by the use of saponins or saponin-containing extracts, the use of fungal treatments is: (i) time consuming, as a fermentation period of 5–7 days is required following the urea-ammoniation treatment, (ii) cumbersome and requiring a certain degree of expertise and additional resources, and (iii) is accompanied by a loss of high-value organic matter. Similarly, the present approach has advantages over the entrapment of ammonia by spraying bales of ammonia-treated straw with acids (Borhami *et al.* 1982; Fahmy & Ørskov 1984). The former is less time consuming and easier to perform. In addition, low and variable voluntary intakes have been observed when feeding urea-ammoniated wheat straw treated with acids, possibly due to large amounts of unpalatable ammonium salts formed by the acid treatment (Cloete & Kritzinger 1984). Furthermore, ammonia-nitrogen bound to saponins or saponin-rich extracts might have beneficial effects on microbial fermentation in the rumen (Hussain *et al.* 1996). Although results from the present study (no difference between rumen fermentation kinetics of urea-ammoniated straw treated in the presence or absence of saponins) do not support this hypothesis, the situation could be different under nitrogen-deficient conditions or when a high energy feed is offered. It may be noted that the fermentation kinetic values (Tables 2 and 4) were obtained with a medium rich in ammonia-N (Menke *et al.* 1979; Menke & Steingass 1988; Makkar *et al.* 1995).

Therefore, from the two sources of saponin studied (*Quillaja* saponins and *Yucca* plant extract obtained commercially in a powder form), the *Yucca* plant powder was more efficient at entrapping ammonia-nitrogen to the straw. The use of this powder at 1 g kg^{-1} (mixed in straw) followed by urea treatment (50 g kg^{-1} urea and 400 g kg^{-1} moisture) led to a substantially higher binding of ammonia-nitrogen to the straw which, besides benefiting the animals, will cause less environmental damage, due to a reduction in ammonia losses to the air. The straw so obtained, with relatively high nitrogen, could be an effective supplement for low-nitrogen feed resources, as otherwise excess nitrogen would be excreted in urine as urea, which is energetically expensive for the animal and also pollutes the environment. Further studies need to be carried out *in vivo* on ruminants in order to evaluate the availability of the nitrogen bound to straw and on the possible beneficial effects of these saponins or their degraded products. The beneficial effects could be mediated via their influence on microbial populations (Mader & Brumm 1987; Makkar & Becker 1996) or due to their surfactant properties, which may lead to better nutrient transport across the intestinal membrane (Price *et al.* 1987; Hwang & Damodaran 1994). Urea-ammoniation of straw at a low content of urea (< 40 g kg^{-1}) has been found to be less effective in improving the digestibility of straw, due to insufficient alkalinity because of lower ammonia release. However, in the presence of *Yucca* powder, which has the ability to entrap ammonia, urea-ammoniation of straw at a lower content of urea incorporation might be beneficial, thereby decreasing the cost of the treatment and reducing the loss of nitrogen to the environment. Studies may also be considered in this direction. The

Table 4. *Effect of* Yucca schidigera *plant extract on net gas production, mg substrate truly digested/ml gas produced, true dry matter-, neutral detergent fibre (NDF)- and organic matter (OM)-digestibility and metabolizable energy (ME) of straw, and on the rate* (c) *and potential extent* (b) *of gas production from straw*

	Un	C_1	C_{2a}	C_{2b}	YPH_3	YPH_4	YPA_1	YPA_2	YP_1	YP_2	S.E. (D.E. for error = 9)
Net gas produced (200 mg/24 h)	22·1	26·4	22·6	21·1	26·3	26·3	28·1	27·2	24·2	26·0	1·08
True DM digestibility (%)	40·9	46·1	36·0	37·4	45·2	46·9	47·7	45·6	47·9	47·0	0·83
NDF digestibility (%)	21·1	25·7	17·5	18·9	27·1	26·3	27·7	26·7	27·8	29·4	1·0
OM digestibility (%)	35·8	42·6	36·9	35·9	42·9	43·3	44·2	43·6	41·1	42·7	0·76
ME (MJ/kg of DM)	5·3	6·4	5·5	5·4	6·4	6·5	6·6	6·5	6·1	6·3	0·11
Rate *c* (h^{-1})	0·0273	0·0272	0·0269	0·025	0·0297	0·0303	0·0311	0·0289	0·0291	0·0269	0·001
Potential *b* (ml)/200 mg	49·2	57·2	49·6	47·4	50·4	51·7	54·5	57·0	48·3	57·1	1·06

Un, untreated; C_1 with urea but no saponin; C_{2a} and C_{2b}, saponin extract at 0·75 and 1 g kg^{-1} respectively but no urea; YPH_3, extract (after homogenization) corresponding to 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPH_4, extract (after homogenization) corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPE_1, extract (without homogenization) corresponding to 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YPE_2, extract (without homogenization) corresponding to 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YP_1, 0·75 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea; YP_2, 1 g kg^{-1} powder of *Y. schidigera* plant extract + 50 g kg^{-1} urea.

present study could also have important ramifications beyond the field of animal nutrition; for example, the slow release of ammonia in soil fertilized with urea and a possibly lower amount of urea application.

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