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Improvement of organic matter digestibility along with changes of physical properties of rice straw by chemical treatments*

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ABSTRACT

This study was carried out to study the effects of different chemical treatments on physical properties and digestion of rice straw. Rice straw was treated with sodium hydroxide (NaOH) at 15, 30, 45, 60 or 75 g/kg dry matter, ammonia bicarbonate (NH_4HCO_3) at 30, 60, 90, 120 or 150 g/kg or their combinations (10 or 20 g NaOH/kg and 30, 60 or 90 g NH_4HCO_3/kg), respectively. The relationship between straw digestion and its physical properties was analysed. Treatment with NaOH increased the volumetric weight (VW), swelling capacity (SC), water-holding capacity (WHC), and *in vitro* organic matter digestibility (OMD), and decreased specific porosity (SP) of rice straw linearly. Treatment with NH_4HCO_3 did not significantly affect VW, SC, or SP, but increase OMD linearly and tended decrease WHC. For the combination treatment of NaOH and NH_4HCO_3, there existed significant interactions on SC, SP and OMD. A significant linear correlation was found between OMD and VW, SC, SP, or WHC, when the data for all treatments were analysed. The accuracy of regression equation could be improved by including multiple physical property parameters. It is inferred that change in all physical properties is indicative of improvement in straw digestion after treatment.

KEY WORDS: rice straw, chemical treatment, physical properties, straw digestion

INTRODUCTION

In China, annual yield of rice straw totals currently about 188 million tonnes (Guo et al., 2002). Unfortunately, low nutrient content and poor digestibility of rice straw limit its efficient use in the diets for lactating and growing ruminants. Physical,

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chemical and biological pretreatments have been widely applied to upgrade the crop residues (Han and Garrett, 1986; Chaudhry, 1998). It has been found that alkali treatment may reduce the lignification of straw (Xiao et al., 2001), cleavage the ester and ether linkages between hemicellulose and lignin (Lawther et al., 1996), decrease the crystallinity of cellulose (Goto and Yokoe, 1996; Isogai and Usuda, 1996), and weaken the interlinkage of the silica-covered cuticle with underling tissues (Bae et al., 1997). These changes may result in modified physical properties of straw, reflected by increased swelling capacity and water retention of straw (Goto and Yokoe, 1996), and hence render the treated straw susceptible to attack by rumen cellulolytic microbes (Xu et al., 1993; Chaudhry, 2000; Selim et al., 2004; Liu et al., 2005).

The physical properties that strongly affect fermentation pattern in human colon are mainly the particle size or bulk volume, the surface area characteristics, and the hydration. For example, particle size influences transit time, fermentation, and faecal excretion (Guillon and Champ, 2000). These physical properties can be expressed by volumetric weight, water-holding capacity, etc. (Goto and Yokoe, 1996; Sangnark and Noomhorm, 2004). Measurement of the parameters for physical properties may quantitatively reveal the mechanism with which to upgrade the crop residues by chemical treatment, and simplify the assessment of treatment efficacy. However there are few systemic studies focused on physical properties and their relationship with nutritive value of cereal straws.

Besides its resourcefulness, ammonia bicarbonate (NH_4HCO_3) is cheaper and decomposes more easily than urea, which is beneficial for inhibition of mould growth during the initial stage of treatment, especially in the rainy season (Liu et al., 1992). However, one may not expect strong effects on physical properties of straw due to its week alkali effect. Sodium hydroxide (NaOH) had strong alkalinity (Han and Garrett, 1986), so the treatment with combination of NH_4HCO_3 plus NaOH may be expected have an optimal effect.

Therefore, this study was conducted to investigate the effects of NaOH, NH_4HCO_3 or their combination treatments on physical parameters of rice straw, such as volumetric weight, swelling capacity, specific porosity and water-holding capacity, and to analyse relationships between physical properties and digestion of straw.

MATERIAL AND METHODS

Preparation and treatment of rice straw

The rice straw used was from the late season rice (va. Yiu64, V_{35}), cultivated in Zhejiang province. Following the harvest, rice straw was air-dried and manually chopped to 3-5 cm lengths. Chopped straw was put into polyethylene bags in three duplicates, and mixed with different dosages of NaOH, NH_4HCO_3, or their combination, respectively. Dosage of NaOH was at 15, 30, 45, 60 and 75 g/kg straw dry matter (DM), respectively. Amount of water used to dissolve NaOH was controlled to adjust the initial moisture content of the treated rice straw to about 40%. After rice straw was thoroughly mixed with NaOH solution, the sealed bags with straw were left in a thermostated container at 35°C for 3 d (Han and Garret, 1986). Dosage of NH_4HCO_3 was at 30, 60, 90, 120 and 150 g/kg DM, respectively, with initial moisture content of the treated straw at about 50%. After rice straw was thoroughly mixed with NH_4HCO_3 solution, the materials were left in a thermostated container at 35°C for 10 d (Liu et al., 1992). To evaluate combination treatments, chopped rice straw was treated with 10 or 20 g NaOH /kg DM at 35°C for 3 d, and then with 30, 60 or 90 g NH_4HCO_3 /kg DM at 35°C for 7 d. Untreated rice straw was used as control.

Measurement of chemical compositions

Untreated and treated rice straw were oven-dried and ground to pass a 1mm sieve for chemical analysis. Contents of crude protein (CP) and ash were determined according to AOAC (1990). Neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) were determined following the procedures by Van Soest et al. (1991). Total silica content was measured directly starting from the ADF procedure of the sequential analysis and termed as acid-detergent insoluble silica (ADISi) after Van Soest et al. (1991).

Measurement of physical properties

The milled samples of untreated and treated rice straws were screened with a 0.45 mm screen, and only the samples on the screen were taken for later analysis to decrease discrepancy (Zhang, 1995; Sangnark and Noomhorm, 2004).

Volumetric weight (VW). Half gram of dry ground samples (W) was put into 10 ml-scaled glass tube. The tube was gently rapped to vent air space, and the volume (V) of samples was recorded. The VW was expressed as the dry weight per volume sample (g/ml).

Swelling capacity (SC). Eight ml of 0.9% NaCl (V_0) was added to a scaled glass tube containing 0.5 gram of dry samples (W) inside. The volume (V_m) of the mixture was recorded after it was stood for 24 h and the air bubbles were vented. The SC was calculated using the equation: SC (ml/g) = $(V_m – V_0)/W$.

Specific porosity (SP). The SP was calculated from the VW and SC, using the following equation: SP (ml/g) = $(V – (V_m – V_0))/W$.

Water-holding capacity (WHC). The dry samples (1.5 g) were weighed into a nylon bag (40 µm mesh, 7 × 12 cm inner size). After being soaked in 0.9 % NaCl at 37°C for 2 h, the bags with samples were centrifugated in a dehydrator at 5000 r/min for 15 min. The weights before (W_{wet}, g) and after drying (W_{dried}, g) at 105°C for 4 h were recorded. Weights of the empty nylon bag before ($W_{wet\ bag}$, g) and after drying ($W_{dried\ bag}$, g) were obtained in the same way. The WHC was calculated as below:

$$\text{WHC (g/g DM)} = ((W_{wet} - W_{wet\text{-}bag}) - (W_{dried} - W_{dried\text{-}bag}))/(W_{dried} - W_{dried\text{-}bag})$$

Estimation of in vitro organic matter digestibility (OMD)

The OMD was estimated from the *in vitro* gas production and crude protein content, which was measured and calculated according to Menke and Steingass (1988). The details for gas test were described elsewhere (Liu et al., 2001).

Statistical analysis

Data for treatment with NaOH or NH_4HCO_3 alone were analysed by one-way analysis of variance, and the results for combination treatment were analysed by two-way analysis of variance, respectively (SAS, 1996). The dosage of chemical was the source of variation in NaOH or NH_4HCO_3 treatment, and orthogonal polynomial contrasts were used to test for linear, quadratic, cubic, and quartic effects of dosage level. Orthogonal polynomial contrasts were also used to test for linear, quadratic effects of NH_4HCO_3 level in combination treatment. The interrelations between physical property parameters and OMD for all treatments were analysed using regression procedure (REG).

RESULTS AND DISCUSSION

Change in chemical compositions of rice straw by different treatments

Changes in chemical compositions of rice straw by NaOH, NH_4HCO_3, and their combination treatment are presented in Tables 1, 2 and 3, respectively. Contents of NDF, ADF, ADL and ADISi were decreased ($P<0.05$), and ash was increased linearly ($P<0.01$) with increasing NaOH dosage. Dissimilar with NaOH treatment, ash was not changed ($P>0.05$), and CP was increased linearly ($P<0.01$) with increasing dosage of NH_4HCO_3. The effects of NaOH on NDF, ADL, CP, and ash, and of NH_4HCO_3 on CP were significant ($P<0.01$) in combination treatment, and that interaction existed between NaOH and NH_4HCO_3 on CP ($P<0.01$). The change in chemical properties of rice straw by different treatments in this study is consistent with other studies (Chaudhry and Miller, 1996; Shen et al., 1998).

Table 1. Effects of sodium hydroxide treatment on chemical compositions, physical properties and *in vitro* organic matter digestibility of rice straw

Item	Dosage, g/kg DM						RMSE[1]	Effect[2]			
	0	15	30	45	60	75		linear	quadratic	cubic	Quartic
Chemical compositions[3], g/kg DM											
NDF	727	695	680	644	609	576	17.2	**	NS	NS	NS
ADF	536	506	502	494	479	462	8.3	**	NS	*	NS
ADL	70	58	62	56	54	54	5.6	**	NS	NS	NS
CP	55	66	57	61	57	56	2.8	NS	*	*	*
ADISi	71	69	69	64	69	63	3.4	*	NS	NS	NS
ash	123	147	151	160	181	180	11.2	**	NS	NS	NS
Physical properties[4]											
VW, g/ml	0.21	0.21	0.22	0.22	0.25	0.22	0.012	**	NS	NS	*
SC, ml/g	0.85	0.87	0.89	1.19	1.29	1.32	0.024	**	*	**	NS
SP, ml/g	3.99	3.86	3.37	3.47	2.87	3.20	0.256	**	NS	NS	NS
WHC, g/g DM	1.69	2.08	1.78	1.93	1.87	1.82	0.093	NS	*	NS	**
OMD[5], g/kg	313	368	432	482	483	513	8.6	**	**	NS	**

[1] root mean squares error; [2] **P<0.01, * P<0.05; NS = not significant; [3]NDF = neutral detergent fibre, ADF = acid detergent fibre, ADL = acid detergent lignin, CP = crude protein, ADISi = acid-detergent insoluble silica; [4] VW = volumetric weight, SC = swelling capacity, SP = specific porosity, WHC = water-holding capacity; [5]*in vitro* organic matter digestibility

Table 2. Effects of ammonia bicarbonate treatment on chemical compositions, physical properties and *in vitro* organic matter digestibility of rice straw

	Dosage, g/kg DM						RMSE[1]	Effect[2]			
	0	30	60	90	120	150		linear	quadratic	cubic	quartic
								P			
Chemical compositions[3], g/kg DM											
NDF	727	737	725	709	709	701	12.2	**	NS	NS	NS
ADF	536	539	537	519	512	508	10.4	**	NS	NS	NS
ADL	70	57	61	59	58	54	4.4	**	NS	NS	NS
CP	55	60	71	90	93	101	4.1	**	NS	*	NS
ADISi	71	71	69	68	72	66	1.9	*	NS	NS	**
ash	123	121	126	120	124	125	6.4	NS	NS	NS	NS
Physical properties[4]											
VW, g/ml	0.21	0.18	0.21	0.19	0.20	0.21	0.016	NS	NS	NS	NS
SC, ml/g	0.85	0.88	0.87	0.88	0.88	0.87	0.014	NS	NS	NS	NS
SP, ml/g	3.99	4.68	4.04	4.23	3.96	3.78	0.355	NS	NS	NS	NS
WHC, g/g DM	1.69	1.75	1.70	1.61	1.61	1.56	0.066	**	NS	NS	NS
OMD[5], g/kg	313	346	348	387	384	414	12.6	**	NS	NS	NS

[1] root mean squares error; [2] **P<0.01; * P<0.05, NS = not significant; [3]NDF = neutral detergent fibre, ADF = acid detergent fibre, ADL = acid detergent lignin, CP = crude protein, ADISi = acid-detergent insoluble silica; [4] VW = volumetric weight, SC = swelling capacity, SP = specific porosity, WHC = water-holding capacity; [5]*in vitro* organic matter digestibility

Table 3. Effects of the combinations of sodium hydroxide and ammonia bicarbonate on chemical compositions, physical properties and *in vitro* organic matter digestibility of rice straw

	Dosage, g/kg DM						RMSE[1]	Effect [2]			
NaOH	10			20				NaOH	NH_4HCO_3		Interaction
NH_4HCO_3	30	60	90	30	60	90			L	Q	
Chemical compositions[3], g/kg DM											
NDF	737	729	724	705	708	699	14.5	**	NS	NS	NS
ADF	517	513	509	508	512	505	5.7	NS	NS	NS	NS
ADL	63	60	60	64	64	68	2.3	**	NS	NS	NS
CP	65	80	80	66	69	71	2.7	**	**	*	**
ADISi	68	67	71	68	67	68	3.1	NS	NS	NS	NS
ash	128	130	129	140	140	138	5.9	**	NS	NS	NS
Physical properties[4]											
VW, g/ml	0.20	0.20	0.20	0.20	0.20	0.23	0.014	NS	NS	NS	NS
SC, ml/g	0.87	0.88	1.12	0.86	0.89	1.25	0.014	**	**	**	**
SP, ml/g	3.68	4.08	4.04	4.15	3.96	3.09	0.242	NS	*	*	**
WHC, g/g DM	1.71	1.72	1.65	1.67	1.72	1.72	0.071	NS	NS	NS	NS
OMD[5], g/kg	336	373	385	395	400	426	7.6	**	**	NS	*

[1] root mean squares error; [2] NaOH = sodium hydroxide, NH_4HCO_3 = ammonia bicarbonate, Interaction = the interaction between NaOH and NH_4HCO_3, L = linear, Q = quadratic; **$P<0.01$, * $P<0.05$, NS = not significant; [3]NDF = neutral detergent fibre, ADF = acid detergent fibre, ADL = acid detergent lignin, CP = crude protein; ADISi = acid-detergent insoluble silica; [4] VW = volumetric weight, SC = swelling capacity, SP = specific porosity, WHC = water-holding capacity; [5]*in vitro* organic matter digestibility

Change in physical properties and digestion of rice straw by different treatments

The analysis of orthogonal polynomial showed that NaOH treatment increased the VW ($P<0.01$), and decreased SP ($P<0.01$) of rice straw linearly (Table 1). Treatment with NH_4HCO_3 did not significantly affect VW, and SP ($P>0.05$; Table 2). The SP was decreased with increasing NH_4HCO_3 ($P<0.05$) in the combination treatment, while the interaction between NaOH and NH_4HCO_3 affected this change ($P<0.01$; Table 3). The effect of NaOH, NH_4HCO_3 or the interaction between them on the VW was not significant ($P > 0.05$; Table 3).

The VW is the weight of material per unit volume, and the SP is indicative of the ratio of the lacuna volume out of cell wall substantiality to the total weight of straw. The change observed in VW or SP may reflect the modification of material structure. The increased VW or decreased SP indicates material contracted, while a decreased VW or increased SP value reflects material expanded (Zhang, 1995). In this study, the significant negative correlation between VW and SP (-0.932) was observed (Table 4). Increase of the VW in NaOH-treated straw may be caused by the high permeation of sodium ion. Although it was reported that liquid ammonia had the ability to form an ammonia-cellulose complex and to decrease the crystallinity of cellulose (Isogai and Usuda, 1992), Goto and Yokoe (1996) observed that gaseous ammonia-treated barley straw had 14% lower ratio of crystalline to amorphous regions than did the untreated straw. Lack of effect of NH_4HCO_3 on VW or SP suggests the weakness of ammonia released from NH_4HCO_3 on straw structure.

Table 4. Correlation coefficients between physical property parameters and *in vitro* organic matter digestibility of rice straw [1]

Correlation	VW	SC	SP	WHC	OMD
VW	1.000	0.696^{**}	-0.932^{**}	0.476^{**}	0.614^{**}
SC		1.000	-0.752^{**}	0.412^{**}	0.789^{**}
SP			1.000	-0.420^{**}	-0.702^{**}
WHC				1.000	0.364^{**}
OMD					1.000

[1] VW = volumetric weight, SC = swelling capacity, SP = specific porosity, WHC = water-holding capacity, OMD = *in vitro* organic matter digestibility, ** $P<0.01$

The SC of rice straw was increased linearly ($P<0.01$) with increasing NaOH dosage (Table 1), but it was not significantly affected by NH_4HCO_3 treatment ($P>0.05$; Table 2). In the combination treatment, the SC was increased with increasing NaOH or NH_4HCO_3 ($P<0.01$), while the interaction existed between NaOH and NH_4HCO_3 ($P<0.01$; Table 3). Treatment with NaOH, an alkali agent, may have increased SC by reducing the lignification of straw, and/or by destruction of the covalent bond between hemicellulose and cellulose (Spencer and Akin, 1980), and/or weakening of the interlinkage of the silica-covered cuticle with underling tissues (Bae et al., 1997).

The WHC was changed quadratically ($P<0.05$) with the dosage of NaOH (Table 1), a maximum value being estimated to be at the 39 g NaOH /kg DM treatment. However, it was decreased linearly ($P<0.01$) with increasing NH_4HCO_3 (Table 2). Alkali treatment opens the fibre structure, making available free hydroxyl groups of cellulose to bind with water. Therefore the WHC appears more likely to reflect the degree to which ester cross-linking between cell wall polymers is disrupted by treatment allowing the wall as a whole, rather than just the cellulose microfibrils to swell (Goto and Yokoe, 1996). The quadratic change in the WHC with NaOH may be dependent on the effect of NaOH on the ester or ether linkage. The WHC of NH_4HCO_3-treated straw obtained in this study was not consistent with results by Goto and Yoke (1996), who showed an increased effect of gaseous ammonia on the WHC of barley straw. This inconsistency may be due to the strict particle size used in this study, and also to the exclusion of leaf blade and leaf sheath materials from the straw samples in their study.

The *in vitro* OMD was increased linearly ($P<0.01$) with NaOH or NH_4HCO_3, either in the single treatment (Tables 1 and 2) or in their combination treatment (Table 3). The increased OMD in pretreated rice straw with NaOH or NH_4HCO_3 are compared with others (Liu et al., 2002).

Correlation between in vitro OMD and physical properties of rice straw

Correlation coefficients between *in vitro* OMD and physical property parameters of straw are presented in Table 4. There was a significant correlation between the OMD and VW ($r=0.614$), SC ($r=0.789$), SP ($r=-0.702$), or WHC ($r=0.364$). The accuracy could be improved by including multiple physical property parameters in the equation (Table 5), as indicated by the decreased residual standard derivation. The VW, SP, and WHC or SC reflects particle size, surface area characteristic, and

Table 5. Relationship between *in vitro* organic matter digestibility and physical properties parameters of rice straw

Equation[1]	R^2	$S_{y,x}$ [2]	P
OMD = 123.4 + 275.6 SC	0.623	28.5	0.0001
OMD = 314.9 + 209.9 SC – 33.6 SP	0.650	28.0	0.0001
OMD = 688.5 + 208.8 SC – 69.8 SP – 1123.8 VW	0.661	27.8	0.0001
OMD = 682.9 + 205.0 SC – 72.1 SP – 1243.0 VW + 24.7 WHC	0.662	27.8	0.0001

[1] OMD = *in vitro* organic matter digestibility, g/kg: SC = swelling capacity, ml/g: SP = specific porosity, ml/g: VW = volumetric weight, g/ml: WHC = water-holding capacity, g/g DM; [2] The residual standard deviation, g/kg

fibre hydration of straw, respectively (Guillon and Champ, 2000; Sangnark and Noomhorm, 2004). Relationship between OMD and these parameters indicates that physical properties are closely related to digestion of straw and may be used to evaluate treatment efficiency.

A close correlation also existed among VW, SP, WHC and SC of straw (Table 4). The increased VW was associated with a decreased SP and increased WHC or SC. The straw with decreased particle size, increased surface area and enhanced fiber hydration may be easily penetrated by the rumen fluid and attached by the rumen microbes (Xu et al., 1993; Goto and Yokoe, 1996; Selim et al., 2002), and hence improved digestion may be expected for the treated straw.

CONCLUSIONS

Treatment of rice straw with NaOH increases volumetric weight, swelling capacity and water-holding capacity, and decreases the specific porosity. Effects of NH_4HCO_3 treatment on physical properties of rice straw are inferior to those with NaOH treatment. Significant correlation exists between *in vitro* organic matter digestibility and physical property parameters. It is concluded that change of physical properties is indicative of improvement in straw digestion after chemical treatments.

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