



Utilization of Rice Straw and Different Treatments to Improve Its Feed Value for Ruminants: A Review

C. Sarnklong, J. W. Cone*, W. Pellikaan and W. H. Hendriks

Animal Nutrition Group, Department of Animal Sciences, Wageningen University,
P.O. Box 338, NL-6700 AH Wageningen, The Netherlands

ABSTRACT : This paper gives an overview of the availability, nutritive quality, and possible strategies to improve the utilization of rice straw as a feed ingredient for ruminants. Approximately 80% of the rice in the world is grown by small-scale farmers in developing countries, including South East Asia. The large amount of rice straw as a by-product of the rice production is mainly used as a source of feed for ruminant livestock. Rice straw is rich in polysaccharides and has a high lignin and silica content, limiting voluntary intake and reducing degradability by ruminal microorganisms. Several methods to improve the utilization of rice straw by ruminants have been investigated in the past. However, some physical treatments are not practical because of the requirement for machinery or treatments are not economical feasible for the farmers. Chemical treatments, such as NaOH, NH₃ or urea, currently seem to be more practical for on-farm use. Alternative treatments to improve the nutritive value of rice straw are the use of ligninolytic fungi (white-rot fungi), with their extracellular ligninolytic enzymes, or specific enzymes degrading cellulose and/or hemicellulose. The use of fungi or enzyme treatments is expected to be a more practical and environmental-friendly approach for enhancing the nutritive value of rice straw and can be cost-effective in the future. Using fungi and enzymes might be combined with the more classical chemical or physical treatments. However, available data on using fungi and enzymes for improving the quality of rice straw are relatively scarce. (**Key Words :** Rice Straw, Characteristics, Utilization, Fungi, Feed, Ruminant)

INTRODUCTION

In tropical zones in the world, ruminants depend on year-round grazing on natural pastures or the animals are fed with cut grass and crop residues. Most of these areas face seasonal dry periods in which the availability of pasture decreases and also its quality by a reduction in the content of digestible energy and nitrogen. Due to the fact that in these areas rice straw is abundantly available from cultivating rice, farmers offer rice straw as the main roughage source to their animals. This is particularly the case in Southeast Asian countries such as Thailand, Vietnam and Indonesia (NARC newsletter, 2004). Feeding only rice straw does not provide enough nutrients to the ruminants to maintain high production levels due to the low nutritive value of this highly lignified material. The high level of lignification and silicification, the slow and limited ruminal degradation of the carbohydrates and the low content of nitrogen are the main deficiencies of rice straw, affecting its

value as feed for ruminants (reviewed by Van Soest, 2006). As rice straw is poorly fermented, it has low rates of disappearance in the rumen and low rates of passage through the rumen, reducing feed intake (Conrad, 1966). By treating rice straw with urea or calcium hydroxide or by supplementing rice straw with protein, intake, degradability and milk yield can be enhanced, compared to feeding untreated rice straw alone (Fadel Elseed, 2005; Wanapat et al., 2009).

In past years, several studies have been reported on the physical and chemical characterization and utilization of rice straw as ruminant feed (Shen et al., 1998; Abou-El-Enin et al., 1999; Vadiveloo, 2000; 2003). In addition, numerous methods of physical, chemical and biological treatments have been investigated, including supplementation with other feed stuffs or components in order to improve the utilization of rice straw by ruminants (Reddy, 1996; Karunanandaa and Varga, 1996a,b; Shen et al., 1999; Vu et al., 1999; Liu and Ørskov, 2000; Selim et al., 2004). Rice straw is usually fed untreated without supplements in spite of the fact that many methods for improved utilization of rice straw have been developed and recommended. There

* Corresponding Author: J. W. Cone. Tel: +31-317-483-542, Fax: +31-317-484-260, E-mail: john.cone@wur.nl

Received November 7, 2008; Accepted December 24, 2009

are several reasons for farmers not to apply the already developed methods for improved utilization of straw, such as physical, socio-economic conditions and practical reasons (Devendra, 1997). In general, the use of rice straw as an animal feed as well as its treatment is always an economic decision.

The aim of this contribution is to provide an overview of existing knowledge on how to treat rice straw to increase its feed value for ruminants. Emphasis is placed on new approaches using enzymes and fungi and combinations of these with other, more classical, treatments, such as physical and chemical treatments.

AVAILABILITY OF RICE STRAW

Agriculture plays a significant role in the world to feed the growing human population. Therefore, land for crop production will be used more intensively for human food production and consequently animal production will rely on feeding the by-products from the food produced for human consumption. This especially will be the case for rapidly growing economies in several parts of Asia, increasing also the demand for meat and milk at a high rate. Thus, many countries in this area urgently need to increase their livestock production.

Many by-products from the human food industry have in common a high biomass, low crude protein content of approximately 3 to 4% and high content of crude fiber of approximately 35 to 48% (Devendra, 1997). In many developing countries these fibrous crop residues, such as cereal straws, sugarcane tops, bagasse, cocoa pod husks, pineapple waste, etc., are usually fed to ruminants.

Approximately 80% of the world's rice is grown by small-scale farmers in many developing countries including South East Asia (Table 1) and it is common to use rice straw for animal feeding. Devendra and Thomas (2002) mentioned that rice straw is the principal crop residue fed to

more than 90% of the ruminant livestock in this area. The calculated utilization of rice straw for animal feed in South East Asia, including China and Mongolia, was 30-40% of the total rice straw production (Devendra, 1997). Rice straw is especially important during periods when other feeds are inadequate. In general, the maximum intake of rice straw by ruminants is about 1.0 to 1.2 kg per 100 kg live weight (Devendra, 1997). In Southeast Asia rice straw is mainly utilized by swamp buffaloes and cattle with adult live weights of 350 and 200 kg respectively (Devendra, 1997). With an average intake of 1 kg of rice straw per 100 kg live weight, this gives a total annual intake of 1.28 and 0.73 t for buffaloes and cattle respectively. The annual requirements for the current populations of swamp buffaloes and cattle are therefore 51.2 and 89.4 million t respectively and a total requirement of 140.6 million t, representing 30.4% of the total annual available rice straw.

GENERAL CHARACTERISTICS OF RICE STRAW

The chemical composition of rice straw

The chemical composition of rice straw varies between varieties and growing seasons, with higher nitrogen and cellulose contents in early-season rice compared to others (Shen et al., 1998). The chemical and mineral compositions of rice straw, from Chinese data, are illustrated in Table 2 and 3.

Nutritive quality of rice straw

Rice straw consists predominantly of cell walls, comprised of cellulose, hemicellulose, and lignin. To break down these components cellulase, hemicellulase and ligninase are required (Schiere and Ibrahim, 1989). These enzymes are not produced by the animals themselves but the reticulorumen of ruminants maintains microorganisms that do produce cellulase and hemicellulase. However,

Table 1. Rice production and obtained residues of the top 10 rice-producing countries in the world in 2003

Number	Country	Rice production (million t)	Rice husk (million t) ^a	Rice straw (million t) ^a
1	China	166.00	38.18	74.70
2	India	133.51	30.71	60.08
3	Indonesia	51.85	11.93	23.33
4	Bangladesh	38.06	8.75	17.13
5	Vietnam	34.61	7.96	15.57
6	Thailand	27.00	6.21	12.15
7	Myanmar	21.90	5.04	9.86
8	Philippines	13.17	3.03	5.93
9	Brazil	10.22	2.35	4.60
10	Japan	9.86	2.27	4.44
Total		506.18	116.42	227.78

^a Calculated data (Adapted from NARC newsletter, 2004).

Table 2. Chemical composition of rice straw in early, middle and late growing season

Cultivation season ^a	DM	N	NDF	ADF	Hemicellulose	Cellulose	ADL ^b	EBSi ^c
	%	% of DM						
Early	96.40	1.04	72.53	43.52	29.01	35.81	4.90	4.82
Middle	96.20	0.99	70.03	41.09	29.08	32.80	4.66	4.57
Late	96.87	0.88	71.97	39.83	32.24	31.96	4.63	4.46
Mean	96.30	0.96	73.01	41.59	31.42	33.35	4.84	4.25
SD ^d	0.86	0.27	3.16	2.17	3.21	1.97	0.44	0.95

^a Season: Early - Transplanting in April, Middle - Transplanting in June, Late - Transplanting in July.

^b ADL: Acid detergent lignin. ^c EBSi: Extractable biogenic silica. ^d SD: Standard deviation.

(Adapted from Shen et al., 1998)

Table 3. Content of total ash, acid insoluble ash and other minerals in rice straw

Cultivation season ^a	Ash	AIA ^b	K	Ca	Mg	P	Na	Fe	Mn
	% of DM								
Early	13.00	2.83	2.21	0.52	0.91	0.13	0.09	0.04	0.07
Middle	13.00	3.85	1.88	0.49	0.30	0.11	0.04	0.04	0.06
Late	10.80	3.49	0.97	0.56	0.23	0.13	0.21	0.11	0.07
Mean	12.10	3.40	1.58	0.53	0.24	0.12	0.13	0.07	0.07
SD ^c	1.46	0.66	0.62	0.11	0.06	0.03	0.10	0.05	0.01

^a Season: Early - Transplanting in April, Middle - Transplanting in June, Late - Transplanting in July.

^b AIA: Acid detergent insoluble ash. ^c SD: Standard deviation.

(Adapted from Shen et al., 1998)

lignin cannot be broken down in the rumen due to the lack of ligninase. Even if lignin could be degraded in the rumen it would not provide much energy for the animals. Lignin, however, has important effects on livestock production through effects on degradability and feed intake. Theoretically, lignin located between the cellulose microfibrils is regarded as the most abundant natural aromatic organic polymer that plays a role in resisting compressing forces, providing protection against consumption by insects and mammals, and also inhibiting the rate and degree of microbial degradation (Iiyama et al., 1990). Silica, one element of the rice cell walls, can be present in high concentrations ranging from 5% to 15%, depending on the rice variety (Vadiveloo, 1992) and the availability of this mineral in the soil (Agbagla-Dohnani et al., 2003). Silica reduces palatability and the degradability of rice straw in the rumen due to its direct action in preventing colonization by ruminal microorganisms (Bae et al., 1997; Agbagla-Dohnani et al., 2003). The role of silica on the quality of rice straw was also reviewed by Van Soest (2006), in an attempt to put into perspective the problems of silicon metabolism.

Besides cell wall polymers, rumen organisms need other nutrients for growth and metabolism (Hoover, 1986). Since rice straw does not contain enough sugars, amino acids and minerals for efficient microbial growth, feeding ruminants with only rice straw, without any supplementation of the other required nutrient sources, will result in poor performance of the animals (Doyle et al., 1986). The

combination of low intake, low degradability, low nitrogen content and an unbalanced mineral composition means that rice straw alone may not even meet the animal's maintenance needs. Poor degradability is caused by a series of factors (Schiere and Ibrahim, 1989). The fiber is very difficult to degrade, which is partly an intrinsic characteristic of the straw fiber. The degradation of the straw fiber is also complicated by the poor functioning of the rumen due to the unbalanced availability of nutrients, the low protein content, the lack of easily available energy and the low content of essential minerals such as P and S. Hence, due to the low degradability and the poor rate of degradation, animals will tend to consume less. The mechanism regulating voluntary intake of low quality feeds, such as rice straw, is still not fully understood. The generally accepted theory of feed intake regulation for poor quality roughages is that the capacity of the rumen to process the feed is the major factor determining voluntary feed intake (Conrad, 1966; Baile and Forbes, 1974). The rumen processing capacity is characterized by rumen fill, the rate of degradation of potentially degradable matter and the rate of passage out of the rumen. Devendra (1997) summarized that the main determinants of intake and degradability of rice straw depend on their morphological characteristics, such as the proportion of the different plant parts (leaves and stems), their chemical composition and the distribution of the different chemical components in the tissues, their relative amounts of cell contents and cell walls and the physical and chemical nature of the cell walls.

These factors influence the chewing behavior of animals and the extent of fragmentation in the reticulorumen.

Rice straw contains a relatively high proportion of leaf (60%), compared to other cereal straws such as barley (35%), oats (43%) and wheat (20-41%) (Theander and Aman, 1984). Leaves of rice straw contain less NDF than the stems, but more ash and acid-insoluble ash, resulting in a lower *in vitro* dry matter digestibility (IVDMD) of the leaves (50-51%) compared to the stems (61%) (Vadiveloo, 2000). In goats, Phang and Vadiveloo (1992) observed an *in vivo* dry matter digestibility of 56.2% for rice leaf and 68.5% for the stem. However, treatment with a 4% urea solution for 21 d increased the IVDMD of the leaf fraction more than that of the stem fraction (Vadiveloo, 2000). Since rice straw consists of approximately 60% leaves (Vadiveloo, 1995), which are less degradable than stems, improving the feed value of rice straw should focus on improving the degradability of the leaves.

POSSIBLE STRATEGIES TO IMPROVE RICE STRAW UTILIZATION

Basically, the key to improving the use of crop residues for ruminants is to overcome their inherent barriers to rumen microbial fermentation. In the case of rice straw, the important factors that restrict bacterial degradation in the rumen are its high levels of lignification and silicification, and its low contents of nitrogen, vitamins and minerals. To improve the feeding value of rice straw, the straw can be treated with different means and methods and other required nutrients can be supplied to the ration of the animal. Strategies to improve the utilization of rice straw are summarized in Figure 1 (after Ibrahim, 1983).

Physical treatment

Crop residues can be ground, soaked, pelleted or chopped to reduce particle size or can be treated with steam or X-rays or pressure cooked. Uden (1988) observed that grinding and pelleting of grass hay decreased dry matter degradability in cows from 73 to 67%, which was mainly due to a decreased fermentation rate (9.4-5.1%/h) and decreased total retention time of the solids from 73 to 54 hours, resulting in an increased intake (Stensig et al., 1994). Liu et al. (1999) reported that the use of steam treatment in a high pressure vessel at different pressures and for a range of different treatment times increased the degradation *in vitro* in rumen fluid after 24 h and the rate of degradation, but could not enhance the potential degradability of the fibrous fractions (NDF, ADF and hemicellulose). Physical treatments of crop residues have received an appreciable amount of research. Many of these treatments are not practical for use on small-scale farms, as they require machines or industrial processing. This makes these treatments in many cases economically unprofitable for farmers as the benefits may be too low or even negative (Schiere and Ibrahim, 1989). However, small machines to grind or chop rice straw may be feasible.

Chemical treatment

Chemicals to improve the utilization of rice straw may be alkaline, acidic or oxidative agents. Among these, alkali agents have been most widely investigated and practically accepted for application on farms. Basically, these alkali agents can be absorbed into the cell wall and chemically break down the ester bonds between lignin and hemicellulose and cellulose, and physically make the structural fibers swollen (Chenost and Kayouli, 1997; Lam et al., 2001). These processes enable the rumen microorganisms to attack more easily the structural

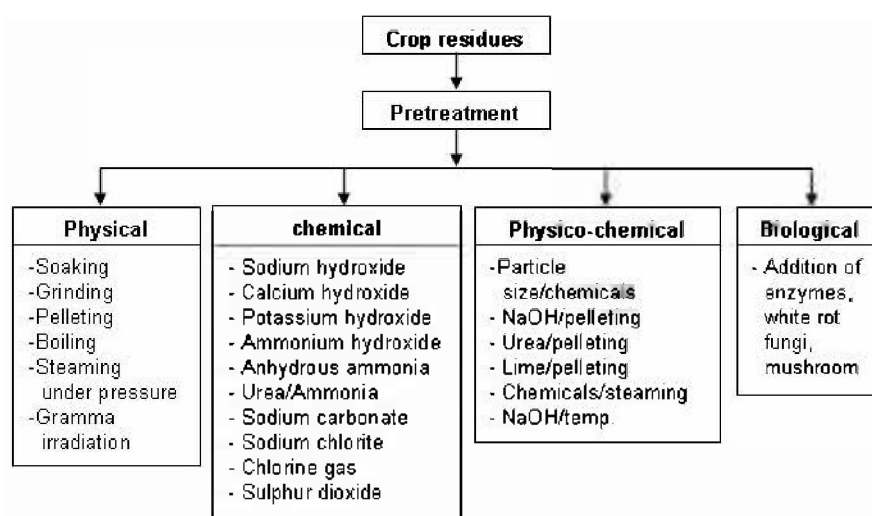


Figure 1. Methods available for treating crop residues (Ibrahim, 1983).

carbohydrates, enhancing degradability and palatability of the rice straw (Prasad et al., 1998; Shen et al., 1999; Selim et al., 2004). The most commonly used alkaline agents are sodium hydroxide (NaOH), ammonia (NH₃) and urea. Chemical treatments appear to be the most practical for use on-farm, as no expensive machinery is required, the chemicals are relatively cheap and the procedures to use them are relatively simple. However, the chemicals themselves are not harmless and safety precautions are needed for their use.

NaOH treatment : Several NaOH treatment methods to improve the use of crop residues for ruminant feeding have been developed as reviewed by Jackson (1977), Berger et al. (1994) and Arieli (1997). The principal advantages of the different NaOH treatment methods are increased degradability and palatability of treated straw, compared to untreated straw (Chaudhry and Miller, 1996; Vadiveloo, 2000). However, NaOH is not widely available as a resource for small-scale farmers and may be too expensive to use. In addition, the application of NaOH can be a cause of environmental pollution, resulting in a high content of sodium in the environment (Sundstøl and Coxworth, 1984).

NH₃ treatment : Treatment of straw with anhydrous and aqueous ammonia, urea or other ammonia-releasing compounds has been widely investigated to improve degradability (Abou-EL-Enin et al., 1999; Selim et al., 2002; Fadel-Elseed et al., 2003). The principle of ammonia treatment is supposed to be similar to that of NaOH treatment. Ammonia treatment not only increases the degradability of the straw, but also adds nitrogen (Abou-EL-Enin et al., 1999) and preserves the straw by inhibiting mould growth (Calzado and Rolz, 1990). Besides, improvement in degradability of structural carbohydrates, ammonia treatment is an effective means of reducing the amount of supplemental nitrogen, reducing the costs of purchasing protein-rich feedstuffs, and enhancing acceptability and voluntary intake of the treated straw by ruminants. Although comparative studies in improving the energy value of straw have shown that ammonia treatment is less efficient than NaOH (Liu et al., 2002), its use may be more profitable for farmers as the added ammonia serves as a source of nitrogen. In a previous study using sheep, Selim et al. (2004) treated rice straw packed in polyethylene bags for 4 weeks with gaseous ammonia (3 g NH₃ per 100 g dry matter). The excess ammonia was removed before offering the straw to animals. The ammonia treatment increased the N content in the rice straw from 8.16 to 18.4 g kg⁻¹ (CP content increased from 51 to 115 g kg⁻¹). The ammonia treatment slightly decreased the NDF content from 571 to 551 g kg⁻¹, because of dilution with the additional N, but increased the ADF content from 303 to 327 g kg⁻¹, indicating that the cell wall properties were changed. Moreover, the physical strength of ammoniated rice straw

was significantly lower than that of the untreated straw. In addition, the proportion of small feed particles tended to be higher and stimulated more attachment and growth of the rumen bacteria (Selim et al., 2002). The reduced particle size and the increased attachment sites could lead to subsequent increased microbial colonization and digestion. So, ammonia treatment increases feed value by making the cell wall more available for the rumen microorganisms and also the increased N content improves microbial growth.

Urea treatment : Rice straw can also be treated with urea, which releases ammonia after dissolving in water. For practical use by farmers, urea is safer than using anhydrous or aqueous ammonia and also provides a source of nitrogen (crude protein) in which straw is deficient (Schiere and Ibrahim, 1989). Since urea is a solid chemical, it is also easy to handle and transport (Sundstøl and Coxworth, 1984) and urea can be obtained easily in many developing countries. In addition, urea is considerably cheaper than NaOH or NH₃. Vadiveloo (2003) reported that rice varieties with a low degradability responded better to urea treatments than higher quality straw, increasing the *in vitro* dry matter degradability from 45 to 55-62%. Urea treatment may therefore be most suitable for small-scale farmers to improve the quality of straws, particularly varieties showing a low degradability. In the past, numerous investigations involving urea treatment of rice straw, with or without additional supplementation, were performed not only in the laboratory (Reddy, 1996; Shen et al., 1998; 1999; Vadiveloo, 2003) but also in field trials (Prasad et al., 1998; Vu et al., 1999; Akter et al., 2004). Pradhan et al. (1997) showed that addition of Ca(OH)₂ to urea improved the IVDMD. Sirohi and Rai (1995) demonstrated that a combination of 3% urea plus 4% lime at 50% moisture for 3 weeks incubation time was the most effective treatment for improving degradability of rice straw. Using urea is regarded as a practical and available method in livestock production, especially in developing countries, as it is relatively cheap, adds nitrogen to the ration and is relatively safe to work with.

Urine treatment : As urine contains urea, urine can be used as a source of urea and ammonia to improve the quality of rice straw. Urine can be sprayed on the straw in a similar way as is done with urea solutions (Dias da Silva, 1993) and can provide a nearly equal improvement of the degradability and nitrogen content as other methods of ammonia treatment (Dias da Silva, 1993; Schubert and Flachowsky, 1994). However, research on this subject has been quite limited and there is currently inadequate information available to define clearly the conditions to optimize urine treatment (Dias da Silva, 1993). Moreover, the use of urine is hampered by the difficulty of separation of urine from feces in ruminant husbandry. This also makes the use of urine rather unhygienic and therefore not

advisable to use, although its use is without costs for farmers and urine is normally available in excess.

Lime treatment : Lime ($\text{CaO}/\text{Ca}(\text{OH})_2$) is a weak alkali agent with a low solubility in water. It has been reported that lime can be used to improve the utilization of straw and also can be used to supplement the ration with calcium, which has been found to be in a negative balance in cattle fed only rice straw (Hadjipanayiotou, 1984; Pradhan et al., 1997; Chaudhry, 1998). Soaking and ensiling are two methods of treating straw with lime. Although lime treatments increase the degradability of straw, the dry matter intake decreases, due to a reduced acceptability of the treated feed by animals. Pradhan et al. (1997) reported that ensiling rice straw with 4 or 6% $\text{Ca}(\text{OH})_2$ showed a higher IVDMD than using 4 or 6% urea. However, mould growth was noticed in the $\text{Ca}(\text{OH})_2$ treated straw. It was suggested that a combination of lime and urea would give better results than urea or lime alone. This combination has the advantage of an increased degradability and an increased content of both calcium and nitrogen. Additive effects of lime and the other alkali agents have been demonstrated (Saadulah et al., 1981; Hadjipanayiotou, 1984). The use of lime may be safer and more cost effective to use than NaOH.

Feeding rice straw supplemented with other components

As rice straw is low in nitrogen and difficult to degrade, it is obvious that supplementation of a ration of rice straw with a protein source and a more easily accessible energy source will improve the performance and production of the animals. Supplementation of a ration of rice straw with protein, energy and/or minerals may optimize rumen function, also maximizing utilization of the rice straw and increasing intake. Chenost and Kayouli (1997) emphasized that it is primarily necessary to supply the rumen microorganisms with the nutritive elements needed for self-multiplication as well as for degradation of the cell walls of straw, leading to suitable conditions for maintenance of good cellulolysis. Different supplements can be used, such as concentrates, molasses, multi-nutrient blocks, green leaves, crop residues and locally available by-products. In the case of high-yielding dairy cows, the supplements can be the major part of the ration where fibrous feed only serves to supply the rumen with enough fiber. Warly et al. (1992) showed in a field trial that a ration of rice straw supplemented with soybean meal increased both degradability and intake. Because of the poor quality of untreated rice straw, supplementation easily can increase milk production, as shown for supplementation with cottonseed meal (Wanapat et al., 1996) and with an urea-molasses-multi-nutrient block (Vu et al., 1999; Wanapat et al., 1999; Akter et al., 2004).

Biological methods

The use of fungi and/or their enzymes (Table 4) that metabolize lignocelluloses is a potential biological treatment to improve the nutritional value of straw by selective delignification, as mentioned in the review by Jalc (2002). Nevertheless, it is currently too early to apply this method in developing countries due to the difficulties and lack of technology to produce large quantities of fungi or their enzymes to meet the requirements. There are also a number of serious problems to consider and overcome (Schiere and Ibrahim, 1989). For example, the fungi may produce toxic substances. It is also difficult to control the optimal conditions for fungal growth, such as pH, temperature, pressure, O_2 and CO_2 concentration when treating the fodder. With recent developments in fermentation technology and alternative enzyme production system, the costs of these materials are expected to decline in the future. Hence, new commercial products could play important roles in future ruminant production systems (Beauchemin et al., 2004).

White-rot fungi treatment : White-rot fungi, belonging to the wood-decaying *basidiomycetes*, as lignocellulolytic microorganisms are able to decompose and metabolize all plant cell constituents (cellulose, hemicellulose and lignin) by their enzymes (Eriksson et al., 1990). Many species of white-rot fungi which are effective lignin degraders have been used to assess their ability to improve the nutritive value of fodder for ruminant nutrition (Yamakava and Okamoto, 1992; Howard et al., 2003). Their extracellular lignin-modifying enzymes consist of lignin-peroxidase (LiP), manganese-dependent peroxidase (MnP), laccase (phenol oxidase) and H_2O_2 -producing oxidase (aryl-alcohol oxidase; AAO and glyoxaloxidase) (Kirk and Farrell, 1987; Arora et al., 2002; Novotny et al., 2004; Arora and Gill, 2005; Lechner and Papinutti, 2006). An overview of investigations using fungi and their determined enzymes is given in Table 4.

Some white-rot fungi are able to decompose free phenolic monomers and to break the bonds with which lignin is cross-linked to the polysaccharides in rice straw (Chen et al., 1996), enhancing IVDMD (Karunanandaa et al., 1992; 1995; Karunanadaa and Varga, 1996a,b; Fazaeli et al. (2006). Karunanandaa et al. (1995) reported the effect of incubation of rice straw for 30 days with three white-rot fungi, showing that *Pleurotus sajor-caju* enhanced IVDMD, in both leaves and stems of rice. However, entire rice straw (leaf and stem) treated with *Cyathus stercoreus* had the highest IVDMD compared to the other fungi (Karunanandaa et al., 1992).

Using white-rot fungi to increase the degradability of straw is often at the expense of easy assessable carbohydrates, such as cellulose and hemicellulose, resulting in less degradable feed for ruminants

Table 4. Fungi and their enzyme production studied to improve the nutritive value of fodder for ruminant feed

References	Species of fungi	Determined enzymes	Main diet ingredients
Jalc (2002)	<i>Phlebia radiata</i> , <i>Coriolus versicolor</i> and <i>Trametes gibbosa</i> <i>Panus tigrinus</i> and <i>Dichomitus squalens</i> <i>Junghuhnia separabilima</i> and <i>Phlebia ochraceofulva</i> <i>Pleurotus ostreatus</i> and <i>Pleurotus sajor-caju</i>	The LiP ^b -MnP ^c The MnP-laccase The LiP-laccase The laccase-AAO ^d	General plant cell wall
Barrasa et al. (1995)	<i>Phanerochaete chrysosporium</i>	Ligninolytic enzyme	Wheat straw
Fazaeli et al. (2006)	<i>Pleurotus</i> fungi	Ligninolytic enzyme	Wheat straw
Barrasa et al. (1995)	<i>T. versicolor</i>	Ligninolytic enzyme	Wheat straw
Rodrigues et al. (2008)	<i>T. versicolor</i> <i>Bjerkandara adusta</i> <i>Fomes fomentarius</i>	MnP, Laccase, CMCas ^e and Avicelase ^f MnP, CMCas and Avicelase Laccase, CMCas and Avicelase	Wheat straw Wheat straw Wheat straw
Kluczek-Turpeinen et al. (2007)	<i>Paecilomyces inflatus</i>	Endoglucanase, xylanase and Laccase	Wheat straw
Eun et al. (2006)	<i>Trichoderma reesei</i>	Cellulase and Xylanase	Rice straw
Zhu et al. (2005)	<i>T. reesei</i>	Cellulase	Rice straw
Giraldo et al. (2007)	<i>T. longibrachiatum</i>	Cellulase	Grass hay
Wang et al. (2004)	<i>T. longibrachiatum</i>	Xylanase and β -glucanase	Wheat straw
Rai and Mudgal (1996)	<i>T. viride</i>	Cellulase	Wheat straw
Giraldo et al. (2007)	<i>Aspergillus niger</i>	Cellulase	Grass hay
Rezaeian et al. (2005)	Fungi from sheep rumen residue	Cellulase and Xylanase	Barley straw
Liu and Ørskov (2000)	<i>Penicillium funiculosum</i>	Cellulase	Rice straw
Eun et al. (2006)	<i>Bacillus licheniformis</i> ^a	Protease	Rice straw
Colombatto et al. (2003a)	<i>B. licheniformis</i> ^a	Protease	Alfalfa hay
Karunanandaa and Varga (1996b)	<i>Cyathus stercoreus</i>	NR	Rice straw

^a One species of bacteria. ^b LiP: Lignin-peroxidase. ^c MnP: Manganese-dependent peroxidase.

^d AAO: Aryl-alcohol oxidase. ^e CMCas: Endoglucanase. ^f Avicelase: Exoglucanase.

NR = Not reported.

(Karunanandaa et al., 1995; Karunanandaa and Varga, 1996a, b; Jalc, 2002). In fact, cellulose and hemicellulose losses during the initial part of incubation with fungi are rather common, but losses due to mycelial growth depend on the fungus species (Table 5). After the initial period of incubation, some white-rot species preferably attack lignin, without degrading cellulose and hemicellulose. Rodrigues et al. (2008) were able to extract the enzymes from white-rot fungi that are responsible for breaking down the bonds in lignin and within the matrix of cell wall carbohydrates, but without also extracting enzymes affecting hemicellulose and cellulose. Using these enzymes on wheat straw the *in vitro* NDF degradability (IVNDFD) increased.

Although the use of fungi to improve the feed value of rice straw is not new, progressing research and new knowledge offers new challenges and possibilities. Fungi can be selected that preferably attack lignin and not the structural carbohydrates in the cell walls. Once these

species are identified, mycologists can breed even better strains. The most desirable situation would be that the mushrooms of the fungi are edible and can be harvested by farmers, after which the remaining straw can be fed to their herd. There are some edible white-rot fungi, like *Pleurotis ostreatus*. However, much research is needed to achieve these goals. The most suitable white-rot species have to be identified and breeding programs will possibly be needed to improve their characteristics. Also, the optimal conditions to incubate straw with a fungus have to be investigated, not only with the purpose of harvesting quality mushrooms, but also achieving optimal feeding quality of the remaining straw-fungi mixture. To achieve optimal feed qualities of the straw, incubations with fungi in combination with other treatments, such as physical and chemical treatments, have to be investigated.

Exogenous fiber-degrading enzyme treatment : Most commercially available exogenous fiber-degrading enzyme

Table 5. Degradation of straw by fungi and enzyme extracts

References	Kind of fungi/enzymes	Kind of straw	Mean degradability untreated control (g/kg)	Change by treatment (g)	Relative change (%)	Degradability method
Kluczek-Turpeinen et al. (2007)	<i>Paecilomyces inflatus</i>	Wheat	357	+14	4	SSF ^a 12 wk, Hemicellulose
	<i>Paecilomyces inflatus</i>	Wheat	239	+49	21	SSF 12 wk, Cellulose
	<i>Paecilomyces inflatus</i>	Wheat	262	+13	5	SSF 12 wk, Lignin
Fazaeli et al. (2006)	<i>Pleurotus fungi 1</i>	Wheat	207	-2	-10	SSF 17 d, Hemicellulose
	<i>Pleurotus fungi 2</i>	Wheat	548	-7	-12	SSF 17 d, Cellulose
	<i>Pleurotus fungi 1</i>	Wheat	207	-2	-11	SSF 17 d, Hemicellulose
	<i>Pleurotus fungi 2</i>	Wheat	548	-5	-8	SSF 17 d, Cellulose
	EE ^c of <i>Trametes versicolor</i> (TV1)	Wheat	349	+10	3	IC ^b 6 d, Hemicellulose
Rodrigues et al. (2008)	EE of <i>T. versicolor</i> (TV2)	Wheat	349	-13	-4	IC 6 d, Hemicellulose
	EE of <i>Bjerkandera adusta</i>	Wheat	349	-16	-5	IC 6 d, Hemicellulose
	EE of <i>Fomes fomentarius</i>	Wheat	349	-15	4	IC 6 d, Hemicellulose
	EE of <i>T. versicolor</i> (TV1)	Wheat	511	-7	-1	IC 6 d, Cellulose
	EE of <i>T. versicolor</i> (TV2)	Wheat	511	+6	1	IC 6 d, Cellulose
	EE of <i>B. adusta</i>	Wheat	511	+7	1	IC 6 d, Cellulose
	EE of <i>F. fomentarius</i>	Wheat	511	+9	2	IC 6 d, Cellulose
	EE of <i>T. versicolor</i> (TV1)	Wheat	104	-3	-3	IC 6 d, Lignin
	EE of <i>T. versicolor</i> (TV2)	Wheat	104	+1	1	IC 6 d, Lignin
	EE of <i>B. adusta</i>	Wheat	104	+1	1	IC 6 d, Lignin
	EE of <i>F. fomentarius</i>	Wheat	104	+7	7	IC 6 d, Lignin
	Liu and Ørskov (2000)	Cellulase	Rice	446	+66	15

^a SSF: Solid-state fermentation. ^b IC: Incubation. ^c EE: Enzyme extract. ^d DM: Dry matter.

products consist of cellulases and xylanases, as produced for non-feed applications. Commercial enzymes used in the livestock feed industry are generally of fungal (mostly *Trichoderma longibrachiatum*, *Aspergillus niger*, *A. oryzae*) or bacterial origin (Table 6). Twenty-two commercial enzyme products were examined for biochemical characteristics and for *in vitro* ruminal degradation of alfalfa hay and corn silages (Comlombatto et al., 2003b). Enzyme treatment alone or in combination with other treatments can increase the degradability of cereal straw by the rumen microorganisms (Liu and Ørskov, 2000; Wang et al., 2004; Zhu et al., 2005; Eun et al., 2006; Fazaeli et al., 2006; Rodrigues et al., 2008) (Table 7). In addition, using fibrolytic enzymes in ruminant feed have shown improvements in the average daily gain of steers (Beauchemin et al., 1995), fleece weight and wool production of lambs (Jafari et al., 2005) and in milk yield of

dairy cows (Yang et al., 2000).

Some studies, using fibrolytic enzymes alone could not significantly increase the degradability of rice straw because the ability of these enzymes to break down the esterified bonds within lignin-carbohydrate complexes may be limited. However, when using in combination with other pre-treatments they could increase degradability and *in vitro* fermentation characteristics, as shown by Eun et al. (2006) who treated with xylanase or cellulase in combination with ammonia, by Liu and Ørskov (2000) who treated with cellulase from *Penicillium funiculosum* in combination with steam pre-treatment, and by Wang et al. (2004) who treated with multi-enzymes (xylanase, β -glucanase, carboxymethylcellulase and amylase) in combination with NaOH. The use of combinations of fibrolytic enzyme with these pre-treatments is expected to have a synergistic effect on the nutritive improvement of rice straw.

Table 6. Degradability of straw by fungi and enzyme extract treatments

References	Kind of fungi/enzymes	Kind of straw	Mean degradability untreated control (g/kg or ml/g)	Change by treatment (g or ml)	Relative change (%)	Degradability method
Fazaeli et al. (2006)	<i>Pleurotus</i> fungi 1	Wheat	281	+12	9	<i>In vitro</i> DM ^a
	<i>Pleurotus</i> fungi 2	Wheat	281	+43	32	<i>In vitro</i> DM
Karunanandaa and Varga (1996b)	<i>Cyathus stercoreus</i>	Rice	371	+16	42	<i>In vitro</i> DM
Eun et al. (2006)	END1 (cellulose)	Rice	153	+14	9	<i>In vitro</i> DM
	END1 (cellulose)	Rice	153	+26	17	<i>In vitro</i> DM
	XY1 (xylanase)	Rice	153	+21	14	<i>In vitro</i> DM
	XY2 (xylanase)	Rice	153	+23	15	<i>In vitro</i> DM
	EX (cellulase+hemicellulose)	Rice	153	+42	27	<i>In vitro</i> DM
	PROT (protease)	Rice	153	+27	18	<i>In vitro</i> DM
	END1 (cellulose)	Rice	170	-18	-11	<i>In vitro</i> , Hemicellulose
	END1 (cellulose)	Rice	170	-9	-5	<i>In vitro</i> , Hemicellulose
	XY1 (xylanase)	Rice	170	-10	-6	<i>In vitro</i> , Hemicellulose
	XY2 (xylanase)	Rice	170	-24	-14	<i>In vitro</i> , Hemicellulose
	EX (cellulase+hemicellulose)	Rice	170	-16	-9	<i>In vitro</i> , Hemicellulose
	PROT (protease)	Rice	170	+50	29	<i>In vitro</i> , Hemicellulose
	END1 (cellulose)	Rice	54 ml g ⁻¹	1 ml	2	GP ^b
	END1 (cellulose)	Rice	54 ml g ⁻¹	1 ml	1	GP
	XY1 (xylanase)	Rice	54 ml g ⁻¹	6 ml	10	GP
	XY2 (xylanase)	Rice	54 ml g ⁻¹	7 ml	13	GP
EX (cellulase+hemicellulose)	Rice	54 ml g ⁻¹	19 ml	35	GP	
PROT (protease)	Rice	54 ml g ⁻¹	11 ml	21	GP	
Rodrigues et al. (2008)	EE ^c of <i>Tramete versicolor</i> (TV1)	Wheat	242 mlg ⁻¹	27 ml	11	GP
	EE of <i>T. versicolor</i> (TV2)	Wheat	242 mlg ⁻¹	65 ml	27	GP
	EE of <i>Bjerkandera adusta</i>	Wheat	242 mlg ⁻¹	15 ml	6	GP
	EE of <i>Fomes fomentarius</i>	Wheat	242 mlg ⁻¹	-4 ml	-2	GP
Liu and Ørskov (2000)	Cellulase	Rice	20 ml	0.3 ml	1	GP
Wang et al. (2004)	Xylanase+β-glucanase	Wheat	134 ml	1.8 ml	1	GP

^a DM: Dry matter. ^b GP: Gas production. EE: Enzymatic extract.

Table 7. Summary of enzyme treatments combined with other treatments of rice straw

References	Kind of fungi/enzymes	Applied with	Mean degradability untreated control (g/kg or ml/g)	Change by treatment (g or ml)	Relative change (%)	Degradability method
Eun et al. (2006)	END1 (cellulase)	3% Ammonia	264	+7	3	<i>In vitro</i> DM ^a
	END1 (cellulase)	3% Ammonia	264	+11	4	<i>In vitro</i> DM
	XY1 (xylanase)	3% Ammonia	264	+36	14	<i>In vitro</i> DM
	XY2 (xylanase)	3% Ammonia	264	+77	29	<i>In vitro</i> DM
	EX (cellulose+hemicellulose)	3% Ammonia	264	+25	9	<i>In vitro</i> DM
	PROT (protease)	3% Ammonia	264	+42	16	<i>In vitro</i> DM
	END1 (cellulase)	3% Ammonia	267	+35	13	<i>In vitro</i> , Hemicellulose
	END1 (cellulase)	3% Ammonia	267	+17	6	<i>In vitro</i> , Hemicellulose
	XY1 (xylanase)	3% Ammonia	267	+52	19	<i>In vitro</i> , Hemicellulose
	XY2 (xylanase)	3% Ammonia	267	+74	28	<i>In vitro</i> , Hemicellulose
	EX (cellulose+hemicellulose)	3% Ammonia	267	+44	16	<i>In vitro</i> , Hemicellulose
	PROT (protease)	3% Ammonia	267	+181	68	<i>In vitro</i> , Hemicellulose
	END1 (cellulase)	3% Ammonia	115 mlg ⁻¹	2 ml	2	GP ^b
	END1 (cellulase)	3% Ammonia	115 mlg ⁻¹	4 ml	4	GP
	XY1 (xylanase)	3% Ammonia	115 mlg ⁻¹	22 ml	19	GP
	XY2 (xylanase)	3% Ammonia	115 mlg ⁻¹	17 ml	15	GP
	EX (cellulose+hemicellulose)	3% Ammonia	115 mlg ⁻¹	13 ml	11	GP
PROT (protease)	3% Ammonia	115 mlg ⁻¹	48 ml	41	GP	
Zhu et al. (2005)	Cellulase	1% NaOH	143	+3	22	IC ^c 70 min, Hemicellulose
	Cellulase	1% NaOH	654	+30	46	IC 70 min, Cellulose
	Cellulase	1% NaOH	060	-10	-162	IC 70 min, Lignin
	Cellulase	Microwave +1% NaOH	102	-1	-10	IC 30 min, Hemicellulose
	Cellulase	Microwave +1% NaOH	692	+34	49	IC 30 min, Cellulose
	Cellulase	Microwave +1% NaOH	049	-9	-180	IC 30 min, Lignin
Liu and Ørskov (2000)	Cellulase	Steam, 15 bar 5 min	532	+26	5	IC 3 wk, DM
	Cellulase	Steam, 15 bar 5 min	25 mlg ⁻¹	1.5 ml	6	GP

^a DM: Dry matter. ^b GP: Gas production. ^c IC: Incubation.

Although, application of enzymes has proven to increase the feed value of poor quality feedstuffs, its use by smallholder farmers is, for the time being, economically unattractive. Especially, the use of lignin-degrading enzymes, originating from fungi, seems a promising development. However, using the fungi themselves, instead

of their isolated enzymes, would be easier and cheaper to apply.

CONCLUSIONS

Although several treatments have been used to improve

the degradability and voluntary intake of rice straw, such as physical or chemical treatments, the practical use of these treatments is still restricted in terms of safety concerns, costs and potentially negative environmental consequences.

Using ligninolytic fungi, including their enzymes, may be one potential alternative to provide a more practical and environmental-friendly approach for enhancing the nutritive value of rice straw. The cost of exogenous enzymes is at present too high to be applied by smallholder farms, but this may change in the future. Moreover, the application of ligninolytic fungi or their enzymes combined with chemical pre-treatments to rice straw may be an alternative way to shorten the period of the incubation times and (or) decrease the amount of chemicals, effecting some synergy. Certainly, since available data on treatments using fungi and their enzymes for improving the quality of rice straw are relatively scarce, these techniques should be developed further.

REFERENCES

- Abou-EL-Enin, O. H., J. G. Fadel and D. J. Mackill. 1999. Differences in chemical composition and fibre digestion of rice straw with, without, anhydrous ammonia from 53 rice varieties. *Anim. Feed Sci. Technol.* 79:129-136.
- Aghagla-Dohmani, A., P. Noziere, B. Gaillard-Martinie, M. Puard and M. Doreau. 2003. Effect of silica content on rice straw ruminal degradation. *J. Anim. Sci.* 140:183-192.
- Akter, Y., M. A. Akbar, M. Shahjalal and T. U. Ahmed. 2004. Effect of urea molasses multi-nutrient blocks supplementation of dairy cows fed rice straw and green grasses on milk yield, composition, live weight gain of cows and calves and feed intake. *Pak. J. Biol. Sci.* 7(9):1523-1525.
- Arieli, A. 1997. Whole cottonseed in dairy cattle feeding: a review. *Anim. Feed Sci. Technol.* 72:97-110.
- Arora, D. S. and P. K. Gill. 2005. Production of ligninolytic enzymes by *Phlebia floridensis*. *World J. Microbiol. Biotechnol.* 21:1021-1028.
- Arora, D. S., M. Chander and P. K. Gill. 2002. Involvement of lignin peroxidase, manganese peroxidase and laccase in degradation and selective ligninolysis of wheat straw. *Int. Biodeterior. Biodegradation* 50:115-120.
- Bae, H. D., T. A. McAllister, E. G. Kokko, F. L. Leggett, L. J. Yanke, K. D. Jakober, J. K. Ha, H. T. Shin and K.-J. Cheng. 1997. Effect of silica on the colonization of rice straw by ruminal bacteria. *Anim. Feed Sci. Technol.* 65:165-181.
- Baile, C. A. and J. M. Forbes. 1974. Control of feed intake and regulation of energy balance in ruminants. *Physiol. Rev.* 54:160-214.
- Barrasa, J. M., S. Camarero, A. T. Martinez and K. Ruel. 1995. Ultrastructural aspects of wheat straw degradation by *Phanerochaete chrysosporium* and *Trametes versicolor*. *Appl. Microbiol. Biotechnol.* 43:766-770.
- Beauchemin, K. A., D. Colombatto and D. P. Morgavi. 2004. A rationale for the development of feed enzyme products for ruminants. *Can. J. Anim. Sci.* 84:23-36.
- Beauchemin, K. A., L. M. Rode and V. J. H. Sewalt. 1995. Fibrolytic enzymes increase fiber digestibility and growth rate of steers fed dry forages. *Can. J. Anim. Sci.* 75:641-644.
- Berger, L. L., G. C. Fahey, L. D. Bourquin and E. C. Tilgeyer. 1994. Modification of forage quality after harvest. In: *Forage Quality, Evaluation, and Utilisation* (Ed. G. C. Fahey). American Society of Agronomy, Inc, Madison, USA. pp. 922-966.
- Calzado, J. F. and C. Rolz. 1990. Estimation of the growth rate of *Pleurotus* on stocked straw. *J. Ferment. Bioeng.* 69:70-71.
- Chaudhry, A. S. 1998. Nutrient composition, digestion and rumen fermentation in sheep of wheat straw treated with calcium oxide, sodium hydroxide and alkaline hydrogen peroxide. *Anim. Feed Sci. Technol.* 74:315-328.
- Chaudhry, A. S. and E. L. Miller. 1996. The effect of sodium hydroxide and alkaline hydrogen peroxide on chemical composition of wheat straw and voluntary intake, growth and digesta kinetics in store lambs. *Anim. Feed Sci. Technol.* 60:69-86.
- Chen, J., S. L. Fales, G. A. Varga and D. J. Roysse. 1996. Biodegradability of free monomeric cell-wall-bound phenolic acids in maize stover by two strains of white-rot fungi. *J. Sci. Food Agric.* 71:145-150.
- Chenost, M. and C. Kayouli. 1997. Roughage Utilisation in Warm Climates. *FAO Animal Production and Health Paper* 135, Rome.
- Colombatto, D., G. Hervas, W. Z. Yang and K. A. Beauchemin. 2003a. Effects of enzymes supplementation of a total mixed ration on microbial fermentation in continuous culture, maintained at high and low pH. *J. Anim. Sci.* 81:2617-2627.
- Colombatto, D., D. P. Morgavi, A. F. Furtado and K. A. Beauchemin. 2003b. Screening of exogenous enzymes for ruminant diets: relationship between biochemical characteristics and *in vitro* ruminal degradation. *J. Anim. Sci.* 81:2628-2638.
- Conrad, H. R. 1966. Symposium on factors influencing the voluntary intake of herbage by ruminants: Physiological and physical factors limiting feed intake. *J. Anim. Sci.* 25:227-235.
- Devendra, C. and D. Thomas. 2002. Crop-animal interactions in mixed farming systems in Asia. *Agric. Syst.* 71:27-40.
- Devendra, C. 1997. Crop residues for feeding animals in Asia: Technology development and adoption in crop/livestock systems. In: *Crop Residuals in Sustainable Mixed Crop/Livestock Farming System* (Ed. C. Renard). CAB International; Wallingford, UK. pp. 241-267.
- Dias da Silva, A. A. 1993. Upgrading of low quality feeds by means of urinary urea. In: *Urine - a Wasted, Renewable Natural Resources* (Ed. F. Sundstøl and E. Owen). NORAGRIC Occasional Papers Series C, Development and Environment Vol. 12:42-49.
- Doyle, P. T., C. Devendra and G. R. Pearce. 1986. Rice straw as a feed for ruminants. *IDP, Canberra, Australia.*
- Eriksson, K-EL, R. A. Blanchette and P. Ander. 1990. *Microbial and enzymatic degradation of wood and wood components.* Springer, Berlin, Heidelberg, New York.
- Eun, J.-S., K. A. Beauchemin, S.-H. Hong and M. W. Bauer. 2006. Exogenous enzymes added to untreated or ammoniated rice straw: Effects on *in vitro* fermentation characteristics and

- degradability. Anim. Feed Sci. Technol. 131:86-101.
- Fadel Elseed, A. M. A. 2005. Effect of supplemental protein feeding frequency on ruminal characteristics and microbial N production in sheep fed treated rice straw. Small Rumin. Res. 57:11-17.
- Fadel Elseed, A. M. A., J. Sekine, M. Hishinuma and K. Hamana. 2003. Effects of ammonia, urea plus calcium hydroxide and animal urine treatments on chemical composition and *in sacco* degradability of rice straw. Asian-Aust. J. Anim. Sci. 16:368-373.
- Fazaeli, H., A. Azizi and M. Amile. 2006. Nutritive value index of treated wheat straw with *Pleurotus* fungi fed to sheep. Pak. J. Biol. Sci. 9(13):2444-2449.
- Giraldo, L. A., M. L. Tejido, M. J. Ranilla and M. D. Carro. 2007. Effects of exogenous cellulase supplementation on microbial growth and ruminal fermentation of a high-forage diet in Rusitec fermenters. J. Anim. Sci. 85:1962-1970.
- Hadjipanayiotou, M. 1984. Effect of level and type of alkali on the digestibility *in vitro* of ensiled, chopped barley straw. Agric. Wastes 10:187-194.
- Hoover, W. H. 1986. Chemical factors involved in ruminal fiber digestion. J. Dairy Sci. 69:2755-2766.
- Howard, R. L., E. Abotsi, E. L. Jansen and S. Howard. 2003. Lignocellulose biotechnology: Issues of bioconversion and enzyme production. Afr. J. Biotechnol. 2:602-619.
- Ibrahim, M. N. M. 1983. Physical, chemical, physico-chemical and biological treatments of crop residues. In: The Utilization of Fibrous Agricultural Residues (Ed. G. R. Pearce). Australian Development Assistance Bureau, Research for Development Seminar three, Los Banos, Philippines, 18-23 May 1981. Australian Government Publishing Service, Canberra, Australia. pp. 53-68.
- Iiyama, K., T. B. T. Lam and B. A. Stone. 1990. Phenolic acid bridges between polysaccharides and lignin in wheat internodes. Phytochem. 29:733-737.
- Jackson, M. G. 1977. Review article: The alkali treatment of straw. Anim. Feed Sci. Technol. 2:105-130.
- Jafari, A., M. A. Edriss, M. Alikhani and G. Emtiazi. 2005. Effects of treated wheat straw with exogenous fibre-degrading enzymes on wool characteristics of ewe lambs. Pak. J. Nutr. 4:321-326.
- Jalc, D. 2002. Straw enrichment for fodder production by fungi. In: The Mycota XI Agricultural Applications (Ed. F. Kempken). © Springer-Verlag, Berlin, Heidelberg. pp. 19-38.
- Karunanadaa, K. and G. A. Varga. 1996a. Colonization of rice straw by white-rot fungi (*Cyathus stercoreus*): Effect on ruminal fermentation pattern, nitrogen metabolism, and fiber utilization during continuous culture. Anim. Feed Sci. Technol. 61:1-16.
- Karunanadaa, K. and G. A. Varga. 1996b. Colonization of rice straw by white-rot fungi: cell wall monosaccharides, phenolic acids, ruminal fermentation characteristics and digestibility of cell wall fiber components *in vitro*. Anim. Feed Sci. Technol. 63:273-288.
- Karunanadaa, K., G. A. Varga, D. E. Akin, L. L. Rigsby and D. J. Royse. 1995. Botanical fractions of rice straw colonized by white-rot fungi: Changes in chemical composition and structure. Anim. Feed Sci. Technol. 55:179-199.
- Karunanadaa, K., S. L. Fales, G. A. Varga and D. J. Royse. 1992. Chemical composition and biodegradability of crop residues colonized by white rot fungi. J. Sci. Food Agric. 60:105-112.
- Kirk, T. K. and R. L. Farrell. 1987. Enzymatic "combustion": The microbial degradation of lignin. Annu. Rev. Microbiol. 41:465-505.
- Kluczek-Turpeinen, B., P. Majjala, M. Hofrichter and A. Hatakka. 2007. Degradation and enzymatic activities of three *Paecilomyces inflatus* strains grown on diverse lignocellulosic substrates. Int. Biodeterior. Biodegrad. 59:283-291.
- Lam, T. B. T., K. Kadoya and K. Iiyama. 2001. Bonding of hydroxycinnamic acids to lignin: ferulic and p-coumaric acids are predominantly linked at the benzyl position of lignin, not the b-position, in grass cell walls. Phytochem. 57:987-992.
- Lechner, B. E. and V. L. Papinutti. 2006. Production of lignocellulosic enzymes during growth and fruiting of the edible fungus *Lentinus tigrinus* on wheat straw. Process Biochem. 41:594-598.
- Liu, J. X. and E. R. Ørskov. 2000. Cellulase treatment of untreated and steam pre-treated rice straw-effect on *in vitro* fermentation characteristics. Anim. Feed Sci. Technol. 88:189-200.
- Liu, J. X., E. R. Ørskov and X. B. Chen. 1999. Optimization of steam treatment as a method for upgrading rice straw as feeds. Anim. Feed Sci. Technol. 76:345-357.
- Liu, J. X., A. Susenbeth and K. H. Südekum. 2002. *In vitro* gas production measurements to evaluate interactions between untreated and chemically treated rice straws, grass hay, and mulberry leaves. J. Anim. Sci. 80:517-524.
- NARC newsletter (rice special issue), May 2004.
- Novotny, C., K. Svobodova, P. Erbanova, T. Cajthaml, A. Kasinath, E. Lang and V. Sasek. 2004. Lignolytic fungi in bioremediation: Extracellular enzyme production and degradation rate. Soil Biol. Biochem. 36:1545-1551.
- Phang, O. C. and J. Vadiveloo. 1992. Effects of varieties, botanical fractions and supplements of palm oil by-products on the feeding value of rice straw in goats. Small Rumin. Res. 6:295-301.
- Pradhan, R., H. Tobioka and I. Tasaki. 1997. Effect of moisture content and different levels of additives on chemical composition and *in vitro* dry matter digestibility of rice straw. Anim. Feed Sci. Technol. 68:273-284.
- Prasad, R. D. D., M. R. Reddy and G. V. N. Reddy. 1998. Effect of feeding baled and stacked urea treated rice straw on the performance of crossbred cows. Anim. Feed Sci. Technol. 73:347-352.
- Rai, S. N. and V. D. Mudgal. 1996. Effect of alkali and (or) steam treatment of wheat straw or cellulase augmented concentrate mixture on rumen fermentation on goats. Small Rumin. Res. 19:219-225.
- Reddy, D. V. 1996. Evaluation of rice straw-poultry droppings based rations supplemented with graded levels of rice bran in fistulated buffaloes. Anim. Feed Sci. Technol. 58:227-237.
- Rezaeian, M., G. W. Beakes and A. S. Chaudhry. 2005. Relative fibrolytic activities of anaerobic rumen fungi on untreated and sodium hydroxide treated barley straw in *in vitro* culture. Anaerobe 11:163-175.
- Rodrigues, M. A. M., P. Pinto, R. M. F. Bezerra, A. A. Dias, C. V. M. Guedes, V. M. G. Gardoso, J. W. Cone, L. M. M. Ferreira, J.

- Colaco and C. A. Sequeira. 2008. Effect of enzyme extracts isolated from white-rot fungi on chemical composition and *in vitro* digestibility of wheat straw. *Anim. Feed Sci. Technol.* 141:326-338.
- Saadulah, M., M. Haque and F. Dolberg. 1981. Treatment of rice straw with lime. *Trop. Anim. Prod.* 6:116-120.
- Schiere, J. B. and M. N. M. Ibrahim. 1989. Feeding of urea-ammonia treated rice straw: A compilation of miscellaneous reports produced by the Straw Utilization Project (Sri Lanka). Pudoc, Wageningen.
- Schubert, R. and G. Flachowsky. 1994. Investigations on nitrogen flow into and out of nylon bag after ruminal incubation and feeding of untreated or ¹⁵N horse urine treated wheat straw in small ruminants. *Anim. Feed Sci. Technol.* 48:199-209.
- Selim, A. S. M., J. Pan, T. Suzuki, K. Ueda, Y. Kobayashi and K. Tanaka. 2002. Postprandial changes in particle associated ruminal bacteria in sheep fed ammoniated rice straw. *Anim. Feed Sci. Technol.* 19:227-287.
- Selim, A. S. M., J. Pan, T. Takano, T. Suzuki, S. Koike, Y. Kobayashi and K. Tanaka. 2004. Effect of ammonia treatment on physical strength of rice straw, distribution of straw particles and particle-associated bacteria in sheep rumen. *Anim. Feed Sci. Technol.* 115:117-128.
- Shen, H. S., D. B. Ni and F. Sundstøl. 1998. Studies on untreated and urea-treated rice straw from three cultivation seasons: 1. Physical and chemical measurements in straw and straw fractions. *Anim. Feed Sci. Technol.* 73:243-261.
- Shen, H. S., F. Sundstøl, E. R. Eng and L. O. Eik. 1999. Studies on untreated and urea-treated rice straw from three cultivation seasons: 3. Histological investigations by light and scanning electron microscopy. *Anim. Feed Sci. Technol.* 80:151-159.
- Sirohi, S. K. and S. N. Rai. 1995. Associative effect of lime plus urea treatment of paddy straw on chemical composition and *in vitro* digestibility. *Indian J. Anim. Sci.* 65:1346-1351.
- Stensig, T., M. R. Weisbjerg, J. Madsen and T. Hvelplund. 1994. Estimation of voluntary feed intake from *in sacco* degradation and rate of passage of DM or NDF. *Livest. Prod. Sci.* 39:49-52.
- Sundstøl, F. and E. M. Coxworth. 1984. Ammonia treatment. In: *Straw and Other Fibrous By-products as Feed* (Ed. F. Sundstøl and E. Owen). *Developments in Animal Veterinary Sciences*, 14. Elsevier, Amsterdam, pp. 196-247.
- Theander, O. and P. Aman. 1984. Anatomical and chemical characteristics. In: *Straw and Other Fibrous By-products as Feed*. (Ed. F. Sundstøl and E. Owen). *Developments in Animal Veterinary Sciences*, 14. Elsevier, Amsterdam, pp. 45-78.
- Uden, P. 1988. The effect of grinding and pelleting hay on digestibility, fermentation rate, digesta passage and rumen and faecal particle size in cows. *Anim. Feed Sci. Technol.* 19:145-157.
- Vadiveloo, J. 1992. Varietal differences in the chemical composition and *in vitro* digestibility of rice straw. *J. Agric. Sci.* 119:27-33.
- Vadiveloo, J. 1995. Factors contributing to varietal differences in the nutritive value of rice straw. *Anim. Feed Sci. Technol.* 54:45-53.
- Vadiveloo, J. 2000. Nutritional properties of the leaf and stem of rice straw. *Anim. Feed Sci. Technol.* 83:57-65.
- Vadiveloo, J. 2003. The effect of agronomic improvement and urea treatment on the nutritional value of Malaysian rice straw varieties. *Anim. Feed Sci. Technol.* 108:33-146.
- Van Soest, P. J. 2006. Review: rice straw, the role of silica and treatments to improve quality. *Anim. Feed Sci. Technol.* 130:137-171.
- Vu, D. D., L. X. Cuong, C. A. Dung and P. H. Hai. 1999. Use of urea-molasses-multinutrient block and urea-treated rice straw for improving dairy cattle productivity in Vietnam. *Prev. Vet. Med.* 38:187-193.
- Wanapat, M., A. Petlum and O. Pimpa. 1999. Strategic supplementation with a high quality feed block on roughage intake, milk yield and composition and economic return in lactating dairy cows. *Asian-Aust. J. Anim. Sci.* 12:901-903.
- Wanapat, M., S. Polyrach, K. Boonnop, C. Mapato and A. Cherdthong. 2009. Effect of treating rice straw with urea and calcium hydroxide upon intake, digestibility, rumen fermentation and milk yield of dairy cows. *Livest. Sci.* 125:238-243.
- Wanapat, M., K. Sommart and K. Saardrak. 1996. Cottonseed meal supplementation of dairy cattle fed rice straw. *Livestock Research for Rural Development.* 8(3) (<http://www.fao.org/ag/AGA/AGAP-/FRG/FEEDback/lrrd/lrrd8/3/metha83.htm>)
- Wang, Y., B. M. Spratling, D. R. ZoBell, R. D. Wiedmeier and T. A. McAllister. 2004. Effect of alkali pretreatment of wheat straw on the efficacy of exogenous fibrolytic enzymes. *J. Anim. Sci.* 82:198-208.
- Warly, L., T. Matsui, T. Harumoto and T. Fujihara. 1992. Study on the utilization of rice straw by sheep: Part I. The effect of soybean meal supplementation on the eating and rumination behavior. *Asian-Aust. J. Anim. Sci.* 5:695-698.
- Yamakava, M. and H. A. Okamoto. 1992. Effect of incubation with edible mushroom, *Pleurotus ostreatus*, on voluntary intake and digestibility of rice bran by sheep. *Anim. Feed Sci. Technol.* 63:133-138.
- Yang, W. Z., K. A. Beauchemin and L. M. Rode. 2000. A comparison of methods of adding fibrolytic enzymes to lactating cow diets. *J. Dairy Sci.* 83:2512-2520.
- Zhu, S., Y. Wu, Z. Yu, J. Liao and Y. Zhang. 2005. Pretreatment by microwave/alkali of rice straw and its enzymic hydrolysis. *Process Biochem.* 40:3082-3086.