

THE FEEDING VALUE OF RECONSTITUTED, AMMONIATED  
BARLEY STRAW FOR RUMINANTS

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The University of Manitoba  
by  
A. Subiyatno

In partial Fulfillment of the  
Requirements for the Degree  
of  
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BY

A. SUBIYATNO

A thesis submitted to the Faculty of Graduate Studies of  
the University of Manitoba in partial fulfillment of the requirements  
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MASTER OF SCIENCE

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## ABSTRACT

Two experiments were conducted to evaluate the effect of moisture content in the ammoniation of barley straw and its nutritive value for ruminants.

Experiment I consisted of two trials. In the first trial, four lambs were assigned in a 4 x 4 latin square design. Animals were fed straw and barley grain at 76.2 and 23.8% of dietary feed intake, dry matter (DM) basis. The type of straws offered were: non ammoniated (NA), dry ammoniated (DA), ammoniated after being reconstituted to 27% (RA-27) and 37% (RA-37) moisture. Urea ( $10.4 \text{ kg}^{-1}$  DM complete feed) was added in the grain for animals consuming A. The effect of treatments was determined by measuring voluntary feed intake, digestibility and nitrogen (N) balance in the lambs. In the second trial, straw samples were incubated in the rumen of three steers using nylon bag technique. Samples were incubated for 0, 2, 4, 6, 12, 24 and 48 hr and withdrawn from the rumen at the same time. The degradability of DM, neutral detergent fiber (NDF), acid detergent fiber (ADF) and crude protein (CP) were determined.

In experiment II, the effect of protein and energy supplementation of barley straw reconstituted to 27% moisture and ammoniated was investigated in a randomized block design. Forty lambs were factorially assigned to four diets for an intake measurement. Sixteen lambs were held

for subsequent digestibility and N balance measurements. Ammoniated straw was fed at 65.0% of dietary intake (DM basis). The remaining diet was supplied by concentrate formulated to contain a combination of rapidly released energy and low undegradable protein (BS), rapidly released energy and high undegradable protein (BF), slowly released energy and high undegradable protein (CF) and slowly released energy and low undegradable protein (CS). Corn and barley grain were used as a source of energy, while fish meal and soybean meal as a source of protein in the concentrate.

Ammoniation of barley straw in both experiments was done in a stack method covered with plastic sheeting. Anhydrous ammonia was injected at the rate of 3.0 and 3.5% (wt/wt, DM basis) for experiment I and II, respectively.

Stack temperature was increased by reconstitution of straw prior to ammoniation ( $P < 0.01$ ). Reconstitution and ammoniation increased CP and acid detergent insoluble N (ADIN) contents of barley straw, while hemicellulose content was decreased ( $P < 0.01$ ). ADF and glucosamine contents of straw were increased by ammoniation and reconstitution at 37% moisture ( $P < 0.05$ ). With the exception of CP, dry ammoniation did not significantly affect the chemical composition of barley straw ( $P > 0.05$ ).

No significant difference on straw intake by lambs was found due to treatment ( $P > 0.05$ ). Digestibility of DM and ADF were only increased by ammoniation and reconstitution

at 27% moisture ( $P < 0.05$ ). Ammoniation and reconstitution also increased NDF and hemicellulose digestibility with the greatest values obtained in animals consuming ammoniated straw reconstituted at 27% moisture. Crude protein digestibility of diets was reduced when lambs were fed ammoniated straw ( $P < 0.01$ ). Reconstitution of barley straw prior to ammoniation increased the digestibility of the fiber fractions, but reduced the availability of straw protein for lambs.

Reconstitution to 37% moisture content increased the rapidly soluble DM and ADF fractions of barley straw in the rumen ( $P < 0.01$ ). The potentially degraded DM of barley straw was increased by reconstitution and ammoniation ( $P < 0.05$ ). However, dry ammoniation did not increase straw degradability ( $P > 0.05$ ). Rate of straw degradation in the rumen was not influenced by treatments ( $P > 0.05$ ).

Source of protein and energy supplementation for ammoniated barley straw did not affect intake by lambs ( $P > 0.05$ ). High protein undegradability improved the digestibility of hemicellulose in the diet ( $P < 0.05$ ). CP and ADF digestibility of the diet were not affected by energy supplementation ( $P > 0.05$ ). However, use of corn grain as a source of energy in the concentrate resulted higher DM, organic matter, NDF and hemicellulose digestibility than barley grain did ( $P < 0.01$ ). Corn grain appears to enhance digestibility of diets by providing slow released energy and N in the rumen.

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This thesis is dedicated to the Tjitro-Sudarmo family.

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## ABREVIATIONS

ADF	acid detergent fiber
ADIN	acid detergent insoluble nitrogen
BW	body weight
° C	degree Celcius
cm	centimeter
d	day
CP	crude protein
DM	dry matter
g	grams
hr	hours
kg	kilograms
l	liters
mg	miligrams
MJ	mega Joule
mm	millimeter
µm	Micrometer
N	nitrogen
n	number of observation
NaOH	sodium hydroxide
NE <sub>m</sub>	net energy for maintenance
NDF	neutral detergent fiber
NH <sup>3</sup>	ammonia
OM	organic matter
psi	pound per square inch
r.p.m.	revolutions per minute

SE	standard error of means
VFA	volatile fatty acid
wt	weight

## INTRODUCTION

Cereal straws are produced in surplus in the world. A low nutritional quality is responsible for the underutilized state of these straws. The potential of this crop residue as an alternative feed for ruminants is currently being realized as cereals and other plant products are grown primarily for human consumption, especially in densely populated areas. There have been many methods developed to upgrade the nutritional quality of cereal straw with focus mainly directed to improved intake and digestibility.

Ammoniation is a well applied method among several techniques designed to improve the nutritive value of low quality roughages by chemical treatments. This method is relatively easy to operate at the farm scale and less costly. A procedure regarding the practical application has been described by Sundstol et al. (1978).

A marked increase in nitrogen (N) content after treatment is one characteristic of ammoniated straw. However, the majority of the N in ammoniated straw is water soluble (Gordon and Chesson 1983) and may be lost after treatment has been completed. Increased moisture levels in straw enhance the binding of ammonia and straw, resulting in a higher N retention (Waiss et al. 1972). Intake of straw by animals is usually increased following ammoniation (Saenger et al. 1983; Streeter and Horn 1984).



The increased intake is apparently a result of increased fragility (Zorrilla-Rios et al. 1985) and digestibility of straw. Dryden and Kempton (1983) found increased digestibility in vivo in barley straw after ammoniation from 42.0 to 60.0% and from 48.0 to 67.0% for dry matter and cell wall organic matter, respectively. Increases of cell wall digestibility is mainly due to an increase in the solubilization of hemicellulose by ammonia treatment (Streeter and Horn 1984).

Ammoniated straw has been used both as the sole dietary ingredient and in combination with concentrates. Results showed that ammoniated straw as the sole dietary energy and protein source has the potential to maintain liveweight of Friesian heifers (Orskov et al. 1983), sheep, steers and bulls (Silva et al. 1989). In combination with concentrate, ammoniated straw has shown superiority relative to nonammoniated straw in producing milk (Orskov et al. 1988). However, in overall performances the animals responses to ammoniated straw were still lower than if they were fed good quality roughages.

Despite the increase of N and fiber digestibilities, ammoniated straw lacks some of the amino acids and energy required to support both rumen microbial and host animal needs at a production level. A protein and energy supplement must be included in ammoniated straw based diets if rapid growth or increased animal performance is desired.

The first experiment of this study was intended to

evaluate the effect of moisture levels prior to ammoniation of barley straw on intake, digestibility and N balance in lambs and to examine rumen degradation of these straw in steers. The second experiment was conducted to assess the effect of source of protein and energy supplement on intake, digestibility and N balance in lambs fed reconstituted, ammoniated barley straw.

## LITERATURE REVIEW

### Potential of Cereal Straw as a Feedstuff

By definition, straw is the above ground part of the cereal plant after the grain has been removed (Staniforth 1979). Intensive use of land for cereal production systems in most countries guarantees a continuous supply of straw. Cereal straw from America and Europe mostly consists of wheat straw, barley straw, oat straw, rye straw and corn stover; while rice straw is mostly produced in Asia. Tremendous amounts of cereal straws are produced, both in developed and in developing countries. According to Kosilla (1984) the world production of cereal straw in 1981 was 2,941,482 thousand tonnes. Compared with the production in 1970, the rise of straw production was 61.1% in developed countries and 34.0% in developing countries. The highest rise happened in North and Central America (75.7%). However, as it is a by-product of grain production, not much thought has been given to both quality and quantity of this material as a feedstuff.

Cereal straw can be collected from the field, but because of its bulky characteristic and low market value per unit weight, transportation is generally uneconomical. For feeding purposes the straw must be dry when stored. Sometimes it is difficult to obtain straw with a suitable water content for storage. Inevitably, most straw is left

in the field to be ploughed into the soil or burned. As a matter of fact, the prime reason for the underutilization of straw lies in the characteristic of straw itself. Inherently, straw has very low metabolizable energy and negligible protein, minerals and vitamins.

### Availability of Cereal Straw

Grain yields are known with some accuracy, however, straw yields are mostly estimated from grain yields. Straw to grain ratio is commonly used to calculate the straw yield. The straw to grain ratio has been decreasing since selection and plant breeding were implemented. Based on statistics from the French ministry of agriculture, Staniforth (1979) reported the evolution of straw to grain ratio in France from 1961 to 1973. The ratio has fallen particularly steep for rye (40%). The reduction of straw to grain ratio due to 12 years of breeding and selection for oat, wheat and barley production is 35, 38 and 25%, respectively. Straw to grain ratio is also influenced by the way the grain is harvested. Yields obtained when using a combine harvester will be lower than those for a crop cut by binder.

A surplus of more than seven million tonnes of cereal straw per year is reported in United Kingdom (Butterworth 1985). In France, seventeen million tonnes out of the

twenty six million tonnes of straw produced is not used annually (Laurent et al. 1985). Reports from United States (Males 1987) have suggested that half of the available barley, wheat and oat straws could provide wintering feed for 17.5 million brood cows, which represents approximately one half of beef cow herd in the United States. The amount of wheat barley and oat straw produced in the United States in 1984 was 104,037 thousand tonnes. There is no data on the state of cereal straw utilization in Canada. However, it is obvious that Western Canada has a great supply of cereal straw (table 1).

Traditionally, straw has been used as animal feed, animal bedding and raw material for paper. However, only a limited amount has been utilized for these purposes. Burning straw after harvest has been and continues to be a popular method used to get rid the excess.

Unlike the yield, the value of straw is independent from that of the grain. In most cases, straw occurs in surplus and, therefore, is worth the cost of collection. Mowat and Wilton (1984) estimated the relative value of grain and straw in Canada generally ranged from 3:1 to almost infinity to one.

Currently, there is world wide interest in utilizing straw as an alternative feed for ruminant animals. This trend can give significant benefits in some conditions. Burning straw has been reported to contribute to atmospheric pollution and road accidents from the smoke

Table 1. Estimation of cereal straw production (thousand of tonnes) in Western Canada in 1986.<sup>¶</sup>

Type of straw	Province				Total
	Manitoba	Saskatchewan	Alberta	B.C	
Wheat	6,716.2	27,555.0	10,818.0	126.0	45,215.2
Oat	601.9	982.8	1,885.0	74.1	3,543.8
Barley	2,221.2	4,807.2	8,622.0	208.8	15,859.2
Rye	122.0	573.2	407.0	15.2	1,117.4
Corn	122.0	-	34.6	-	156.6
Total	9,783.3	33,918.2	21,766.6	424.1	65,892.2

<sup>¶</sup> Based on data of 1986 grain production (Canadian Grain Commission 1987). The amount of straw is calculated by multiplying grain production to factor of 1.5 for wheat, 1.3 for oats, 1.2 for barley, 2.0 for rye and 2.0 for corn (Kossila 1984).

produced. As a result, most of the developed countries have introduced a number of regulations to control straw burning.

Utilization of straw as a feedstuff is a more acceptable way to dispose of excess by-product from cereal grain production than burning. Straw can also fill the space for fiber requirements in the formulation of high energy diets. Crop failure, resulting from unfavorable environmental conditions such as drought, in livestock producing areas has resulted in increased demand for straw as an alternative fiber and energy sources. In parts of the world where grain is grown primarily for human consumption, cereal straw utilization by livestock is the most feasible farming system. Competition for land between animals and human population can be avoided by using straw as a basal food for the feeding system.

Ruminants are equipped with a large fermentation compartment in their gastrointestinal tract, in which microbes can convert fiber to volatile fatty acids. If this capability can be exploited, ruminants will be able to utilize relatively cheap energy sources such as straw for production.

Faulkner et al. (1985) found that drylot cows with an average body weight of 531 kg were capable of consuming 14.9 kg ammoniated straw dry matter per day without losing weight. From data shown (table 1) it can be expected that Western Canada cereal straw can feed at least 12 million

mature cows. The Canadian cow population in 1987 is 7.9 millions (Agriculture Canada 1988). Based on these statistics, it appears unavoidable that a large percentage of straw will be left in the field. This remaining straw can be utilized to prevent soil erosion and maintain soil quality.

### Nutritional Characteristics of Cereal Straw

Cereal straws have more gross energy than their corresponding grain (National Research Council 1985). However, the value of straw as a source of feed energy is low. The digestibility of straw is low due to its high content of lignin (Van Soest et al. 1984). Usually straw is used as a feed when other roughage is unavailable.

The cell wall accounts for a large proportion of the dry matter in straw, often exceeding 80%. It consists of structural carbohydrates, aromatic material (including lignin) and silica. The proportion of protein, soluble carbohydrate and minerals other than silica in general is low (table 2).

Structural Carbohydrates. Based on the chemical composition and the solubility properties in various reagents, plant cell walls contain three types of



Table 2. Average values for nutrient composition of cereal straws (DM basis).<sup>¶</sup>

Cereal straw	CP	Cellulose	Hemicel- lulose	Lignin	Ash	Ferulic +couma- umaric acid mg g <sup>-1</sup>
	%	%	%	%	%	
Barley	4.1	44.0	27.0	7.0	6.0	NA <sup>§</sup>
Oat	5.9	41.0	16.0	11.0	5.9	9.4
Rice	4.2	33.0	26.0	7.0	18.9	NA
Wheat	3.6	39.0	36.0	10.0	6.1	6.7
Maize stover	6.6	25.0	NA	11.0	5.7	NA
Sorghum stover	5.3	31.0	30.0	11.0	10.6	NA
Rye	3.2	NA	NA	NA	3.9	NA

<sup>¶</sup> Compiled from Jackson (1977), National Research Council (1985) and Hartley (1987).

<sup>§</sup> NA: Data not available.

structural polysaccharides, namely cellulose, hemicellulose and pectic polysaccharide (Theander and Aman 1984). Cellulose and hemicellulose are usually referred to as structural carbohydrates.

Cellulose constitutes 20-40 % of the dry matter of all higher plants and is the most abundant molecule in the world (VanSoest 1982). Composed of up to 10,000  $\beta$  1,4-linked glucopyranosil units in a linear polymer, the molecule is complicated by its three-dimensional structure. In nature, it occurs largely in crystalline form, organized as fibrils, where the cellulose chain is tightly packed together in compact aggregates surrounded by a matrix of other cell wall constituents such as silica and lignin. The glucan chains are held together by hydrogen bonds between sugar units. (Theander and Aman 1984). The nutritional availability of cellulose varies from total indigestibility to complete digestibility, depending largely upon lignification, silification, cutinification and intrinsic properties of the cellulose itself (Van Soest 1982). Treatment such as milling, steaming or swelling with chemicals can increase accessibility of cellulose to hydrolysis and thus increase its digestibility.

The hemicellulose content of cereal straw ranges from 16 to 36% of the dry matter (table 2). Van Soest (1982) describes the hemicellulose structure as a mixture of polysaccharides linked by  $\beta$  1,4-linkages in the main xylan core polymer and some branches of glucosidic linkages. The

nutritional availability of hemicellulose is also dependent to its association with lignin. There is evidence that the phenolic compound, lignin, is bound with hemicellulose in ester linkages to xylose and possibly glucosidic linkages. These linkages are susceptible to alkaline attack.

Lignin. Together with structural carbohydrates, lignin protects plants against destruction by providing strength to cell wall. Lignin is a non carbohydrate, but has always been discussed together with structural carbohydrates because of its close association with cellulose and hemicellulose in plant cell wall. Knowledge of forage lignin content is of particular importance when estimating feed value. There is evidence that lignin content is strongly negatively correlated with dry matter and fiber digestibility (Allison and Osbourne 1970).

Structurally, lignin is synthesized from phenylpropane units, which have been identified as p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol (Theander and Aman 1984). Arrangement of lignin molecules is the major factor in reducing digestibility. Lignin linkages with carbohydrate are mainly with hemicellulose. Linkage with cellulose is probable, but lacks demonstration because of difficulty in preparing soluble derivatives that can be characterized (Van Soest 1982). Hartley (1972) demonstrated that treatment of the cell walls of grasses with fungal

cellulase releases ferulic acid component that is ester-linked to the hemicellulosic side chain of xylose and arabinose. Analytical results (Jung and Vogel 1986) suggest that the direct association between hemicellulose and lignin causes greater inhibition of hemicellulose digestion due to increasing lignin concentration than of cellulose digestion. Experiments with chemically delignified forages generally indicate that removal of lignin improves hemicellulose digestibility to a greater degree than of cellulose. However, Bunting et al. (1984) reported that cellulose digestibility is increased more than hemicellulose with delignification by ozone treatment.

Van Soest (1982) reported that lignin in all forages contains nitrogen. Heating of forages during storage was reported to cause binding between lignin and nitrogen which will be recovered in the acid detergent fiber determination. The nitrogen content of acid detergent fiber is positively correlated with lignin content and negatively with digestibility (Van Soest 1982).

Lignin, by its nature is resistant to hydrolytic cleavage in the digestive system, but very labile to oxidation. Mild alkali treatment can cleave the ester linkages between lignin and carbohydrates (Jackson 1977). Chesson et al (1983) suggested that ester bonds between cell wall carbohydrates and phenolic monomers or polymers could be hydrolysed with alkali to improve forage digestibility. Removal of lignin has the effect of removing

much of the ionic structure of the plant wall structure thereby reducing the cation exchange capacity of the matrix. Exchange capacity affects the hydratability of the cell wall surface, and probably microbial attachment and induction of fermentation (Mc Burney et al 1981).

Another theory to explain the reduced digestibility associated with increasing lignin content is that the hemicellulose-degrading enzymes may not recognize the ligno-hemicellulose complexes as substrate and be unable to degrade them. Alternatively the phenolic nature of lignin itself may act as an inhibitor of the enzymes since most phenols are known to be enzyme inhibitors (Morrison 1983).

Crude Protein. The content of crude protein in straw is low (table 2). Higher values may be obtained when crops are grown under cold and wet conditions where they do not mature completely. Variation in protein content may also result from differences in type of soil ,the level of fertilizer applied and influence of drought. A major part of the protein in cereal straw is likely associated with the cell walls. Cell wall proteins are known to have low digestibility (Theander and Aman 1984).

It has been known that fiber fermenting microorganisms in the rumen need some nitrogen for synthesis of their body protein. Giving straw as the only feed will not meet the requirements of protein for both microorganisms and the

ruminant itself. Addition of nitrogen from non protein nitrogen sources such as urea or true protein in concentrate feed could enhance cellulose and hemicellulose digestion.

Silica. The mineral content of cereal straws vary widely depending on agronomical factors and soil contamination. Characteristically, straw has low phosphorus, marginal calcium and high silica content. It is interesting to note that rice straw has an ash content three times as high as other straws. Rice straw contains much more silica (13%) and less lignin (7%) than other straws which contain 3-6% silica and 7-11% lignin (Jackson 1977). Silica is taken up by the plant roots from the soil as monosilicic acid,  $\text{Si}(\text{OH})_4$ , and transported to the shoots. When water is lost by transpiration, silica is deposited in cell-walls where it occurs in opaline form ( $\text{SiO}_2 \cdot n\text{H}_2\text{O}$ ,  $n=0.4-0.8$ ) (Jones et al. 1963).

Van Soest and Jones (1968) indicated that silica reduced palatability and degradability of polysaccharides in the rumen, however, the mechanism is not entirely understood. Probably silica acts as a barrier to microbial degradation (Hogan and Weston 1971). Like lignin, silica is rendered soluble by alkali treatment.

## Methods of Improving Straw Utilization

Untreated straw has been traditionally fed to ruminants especially when a shortage of roughage occurs. Without protein and energy supplementation straw, is expected to give poor performance when used for production of meat or milk. Although the gross energy of straw is high it is provided by cellulose and hemicellulose which are not readily available for digestion by rumen microorganisms. In addition, the protein content of straw is inadequate for support of optimum microbial activity. The digestive enzymes of ruminant cannot break down the major carbohydrate components of roughage, therefore, the goal of any feeding program utilizing straw should be to maximize microbial digestion and utilization of ingested material.

### Physical Treatment

Reducing particle size by grinding, milling, chopping or compaction is one of the major ways to improve the nutritive value of straw. This process generally results in an increase of dry matter intake by animals. One factor contributing to increased dry matter intake due to physical treatment is an increased density of the feedstuff which in turn decreases the chewing time required to reduce ingested material to a particle size suitable for digestion by rumen

microorganisms (Walker 1984). To enhance microbial digestion of cellulose and hemicellulose in the rumen, an accessible surface is required. Only extreme milling treatment can actually disrupt fiber structure at the polymer level which is capable of increasing the digestibility of carbohydrate to any considerable extent (Dehority and Johnson 1961). Grinding only moderately increases available surface area because of the length to width relationship of fibers. Owen (1978) has noted that a clear advantage of grinding straw is that it can be readily incorporated into complete feed.

Compaction processes such as pelleting or cubing usually follow grinding or milling of straw. These processes add some benefit namely: increased density, reduced dust, improved handling ease and reduced waste. Alawa and Owen (1984) have reported that pelleting and cubing of wheat straw improved intake of dry matter and organic matter but caused a depression in dry matter digestibility in the sheep. A general finding has been that the reduction in size of coarse materials increases the fine particles that may pass through the digestive track too rapidly for maximum nutrient utilization. In addition mechanical treatment usually requires high investment inputs for machineries and energy.

Steam treatment is another method to improve straw nutritive value. This technology is based on the hydrolytic action of high temperature steam which breaks chemical



bonds and causes fiber degradation that increase digestibility of straw. Walker (1984) summarized the characteristic of this process, including: the production of acetic and other acids, production of furfurals and phenolic derivatives, destruction of the hemicellulose fraction to varying degrees and dry matter losses of 1-20% of starting material due to steam solubilization. Steaming crop residues at very high pressure may increase digestion inhibitors. Oji and Mowat (1978) found a 70% increase of apparent lignin content in corn stover treated in a digester extruder at 16.6 kg/cm<sup>2</sup>, 205° C for 15 minutes. This was due to formation of artifact lignin from the nonenzymatic browning reaction. Although the procedure of this treatment is simple, high initial capital requirements limits the application of this technology.

Another treatment which has been tried at the laboratory scale is irradiation. When straw is irradiated, the cellulose chain length is reduced and the insoluble carbohydrate component becomes more available to rumen bacteria (Walker 1984). Yu et al. (1975) reported that cell wall digestibility by rumen microorganisms decreases sharply at dosages greater than 100 Mrad. Apparent digestibility increases, however, Yu et al. (1975) suggested this was due to hemicellulose solubilization. A presence of inhibitory compounds generated by the irradiation process or a change in the general intractability of the nonsolubilized cell wall residues is

suspected. Only a limited number of irradiation studies have been reported to upgrade crop residues for ruminant feed use.

### Chemical Treatment

Hydrolysis of the ester linkages between lignin, cell wall polysaccharide, cellulose and hemicellulose is the main purpose of chemical treatment. As a result, more carbohydrate is expected to be available to the microorganisms in the rumen. All the chemical methods currently being developed use alkali compounds, such as: sodium hydroxide (NaOH), ammonia (NH<sub>3</sub>), calcium hydroxide (Ca(OH)<sub>2</sub>) or their equivalent products.

In terms of increasing the digestibility of straw after treatment, use of NaOH results in the best response. According to Homb (1984) this treatment was developed in Germany during the World War I by Beckman in 1919 and, therefore, is often referred to as Beckman method. Straw is soaked for one to two days in dilute solution (15-30 g/l) of sodium hydroxide, then washed exhaustively to remove residual alkali. The process increases digestibility of straw, however, a considerable proportion of the soluble nutrient is lost in the washing. Later, this process was modified to reduce loss of dry matter and labor. The modified method is referred to as a dry alkali treatment.

Relatively small volumes (100-400 l/tonne DM) of concentrated (20-40%) NaOH is sprayed to the straw. Excess sodium is not removed before feeding. This process can be applied easily at the industrial scale, often combined with physical treatment such as chopping, milling and pelleting.

NaOH treatment increases the digestibility of cellulose by swelling it and dissolving the lignin. The swollen cellulose can be penetrated more readily by rumen microorganism (Jackson 1977). Lesoing et al (1980) suggested that solubilization of hemicellulose in the straw was increased without affecting the solubilization of cellulose.

In nearly all cases an improvement in feed intake has been demonstrated with NaOH treated straw. Increased dry matter intake is associated with a decrease in rumen retention time (Coombe et al. 1979). In vitro and in vivo digestibilities of straw is increased with NaOH treatment. Males (1987) reported that in most cases, the in vitro dry matter disappearance was higher than in vivo dry matter disappearance because NaOH treatment caused a reduction in rumen retention time of the more digestible treated material. Barber et al. cited by Givens et al. (1988) reported that in vitro measurements include solubilized phenolic acid in the digestible fraction despite their not being digested in vivo.

Performance of animals in response to the NaOH treatment is quite variable and appears to be related to

the amount of straw fed in the diet. Animal responses to NaOH treated straw are summarized by Males (1987).

Feeding NaOH treated straw may cause health problems for animals. Kristensen (1984) reported that sodium is excreted in the urine. This Na excretion also drains other minerals. Furthermore, he suggested that extra supplementation of certain minerals such as K, Cl and Mg might be necessary for livestock consuming NaOH treated feedstuff, especially for growing and lactating animals.

The popularity of NaOH treatment to increase feed value of low quality forage has diminished due to rising concern about soil pollution caused by this treatment. Subsequently, ammonia treatment became a viable alternative. Both chemicals are energetically expensive to manufacture and are potentially hazardous for on farm handling (Owen et al 1984). Researchers continued to look for more suitable methods for farm scale application.

Calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) has been substituted for NaOH. Compared with NaOH, this chemical is much weaker and requires higher moisture and heat to react with the material. Optimum conditions for this treatment are not well defined. Owen et al. (1984) assumed that the mode of action of  $\text{Ca}(\text{OH})_2$  are similar to NaOH treatment if conditions are optimized. Although chemical application rates are greater for  $\text{Ca}(\text{OH})_2$  than for NaOH, the deleterious effects to the animals and the cost are less. Djajanegara et al (1985) reported increases of organic

matter digestion from 54 to 62% and feed intake from 478 g to 839 g when  $\text{Ca}(\text{OH})_2$  treated, 90 g/kg, wheat straw is fed to sheep. This treatment is probably also applicable in developing countries since it could be substituted with soaking straw in lime water (Abou-Raya et al. 1964). Further research is needed to elucidate the optimum treatment conditions.

Potassium hydroxide (KOH) is another alkali that can be used to treat straw to improve its nutritive value. Compared with NaOH use of KOH is expensive for same effectivity when treating straw.

Considering the high potassium content of rice hull it might be possible to use ash of rice straw hull as a source of alkali. This can provide a simple and cheap technology of straw processing in some Asian countries where rice straw is abundant. Currently, there is little information regarding use of this treatment.

### Biological Treatment

In addition to physical and chemical treatment, increasing the nutritive value of straw can be done by utilizing lignolytic organisms. Zadrazil (1984) pointed out that the main problem of biological upgrading of lignocellulose in feed was to find suitable microorganisms with metabolic patterns different from those of rumen flora and fauna. They should have a strong lignin metabolism with

a low degradation of cellulose and hemicellulose.

A group of white rot fungi that fit to the above criteria have been used for conversion of straw into human food. Included in this group are Pleurotus spp and Stropharia rugosoannulata (Zadrazil 1984). Zadrazil (1987) reported that both white rot fungi are very good in decomposing cereal straw lignin. Inoculation of straw with Pleurotus spp increases the digestibility from 40% to 60-65%, while with Stropharia rugosoannulata increases digestibility from 40% to 72%. Burrows et al. (1979) used Coprinus sp for the conversion of straw into ruminant feed. It was found that mycelial growth is stimulated by the addition of inorganic nitrogen. Shortly after inoculation, a large quantity of fungal biomass (mycelium and fruit bodies) was produced, however, lignin was not decomposed and in vitro digestibility increased for a short time only, i.e. maximum 3 days after inoculation.

Unlike the physical and chemical treatments, information regarding biological upgrading of cereal straw is very limited. Zadrazil (1984) summarized results of investigations at the laboratory scale. In vitro digestibility of fungal substrate may increase or decrease, depending on numerous treatment conditions. At present, application of biological methodology is not being practiced.

### Supplementation of Straw Based Diets

The majority of cereal straw produced in developed countries is burned as a waste, however, in developing countries a significant proportion of straw is included in the ruminant diet. Considering the low nutritive value of such feedstuff for production purposes, straw based diets must be supplemented to compensate deficiencies in protein, energy, vitamins and minerals.

Straw fed ruminants rely on rumen microorganisms to provide feed energy derived from the cell wall constituents, since ruminants do not have enzymes for the hydrolysis of cellulose and hemicellulose to the molecule glucose. Glucose is further fermented by a complex series of reactions to give rise to short chain volatile fatty acids (VFA), methane and CO<sub>2</sub> (Preston and Leng 1984). The intermediate of this breakdown together with nitrogenous sources are used for microbial cell production.

Some cellulolytic organisms have requirements for branched chain amino or fatty acids (Helmsley and Moir 1963). Hume (1970) showed that addition of soluble protein increased microbial outflow from the rumen when a purified diet containing urea as the only N source was fed. A continuous supply of ammonia in the rumen seems to be necessary to maintain intake and digestibility. Therefore, the rate of ammonia release in the rumen must be synchronized with the rate of fermentation.

Nolan and Stachiw (1979) reported that sheep fed wheat straw based diets had 50% of microbial-N recycled within the rumen. This might have resulted in death to the microorganisms due to starvation when the rumen supply of fermentable substrate was exhausted. Preston and Leng (1984) suggested that the pattern of feed intake on straw diets may cause microbial populations in the rumen to fluctuate with intermittent death rate and lysis of microbes, especially prior to feeding, largely through lack of substrate. This could lead to low dry matter intake and slow colonization of feed particles by bacteria.

The inclusion of concentrate in straw based diets must not reduce its feeding value. It should create optimum condition for straw fermentation by rumen bacteria as well as providing essential nutrients which compliment and balance the absorbed products of rumen fermentation.

Recently, Silva and Orskov (1988) reported that supplementation of a barley straw diet with unmolassed sugar beet-pulp and dry grass at level of 150 g/kg DM increased barley straw degradation by 9 and 15%, respectively. An attempt to include molasses or dried grass with no nitrogen addition in straw based diets gave no definite effect on live weight change in steers (Mbatya et al 1985b).

Addition of urea also is reported to increase straw dry matter intake. Mbatya et al(1985a) reported that 0.5-1.0 kg urea/100 kg straw DM is the optimum level. However,



a study conducted by Smith et al (1984) showed that fish meal is a more effective N supplement than urea, rapeseed meal or soybean meal in supporting live weight gain of heifers fed a diet containing over 50% barley straw.

Wiedmeier et al (1983) reported increases of fiber digestibility, energy availability, VFA production and microbial number when 81.5% wheat straw diets were supplemented with soybean meal to increase crude protein content from 6.5% to 11.0%. Previous performance trials in the same station (Males et al. 1982) showed that with a high wheat straw diet (80% of DM total diet) improvement of cow performance during the winter is obtained when diets having crude protein contents at least 30% above National Research Council requirements are fed. It is suggested that pre-formed protein as a supplement can optimize utilization of straw (Males 1987). However, this factor is not identified.

#### Ammoniation of Cereal Straw

Sundstol and Coxworth (1984) reported that one of the first systematic studies of the effect of ammonia treatment on straw was carried out in Germany by Kronberger in 1933. Treatment of cereal straw with ammonia gained its popularity after several restrictions on the pollution by NaOH were enforced.

### Nature of Chemicals Used

Ammoniation of straw can be carried out with either direct use of ammonia gas or indirectly with the product of urea hydrolysis. Ammonia, at normal pressure and temperature, is a colorless gas with a penetrating odor. The gas is easily liquified under pressure and dissolved readily in water. At 20° C the vapor pressure is 8.5 atm and the specific gravity at 0° C is 0.63. Boiling point at atmospheric pressure is -33.4° C and freezing point is -77° C. Urea is a crystalline solid produced technically from ammonia and CO<sub>2</sub>. It is also easy to dissolve in water (Sundstol and Coxworth 1984).

Two forms of ammonia commonly used are anhydrous and aqueous ammonia. Anhydrous ammonia is the most concentrated form of chemical and, therefore, small amounts are needed for treatment of straw. It has advantages in providing rapid and homogeneous distribution in the straw. Aqueous ammonia is ammonia dissolved in water. A common solution of aqueous ammonia contains 25% NH<sub>3</sub> by weight. For very dry straw, aqueous ammonia has more advantages over anhydrous ammonia. Water brought by aqueous ammonia helps straw in trapping N and, therefore, reduces NH<sub>3</sub> lost to the air. It is also safer and easier to transport. However, the risk of molding after treatment is increased by the extra water added if the gaseous NH<sub>3</sub> is not equally distributed.

### Mode of Action of Ammonia

The low digestibility of dry matter and fiber in cereal straw is due to an association between lignin and carbohydrates in plant cell walls. Lignin has alkali-labile linkages. Ammonia and other alkali compounds hydrolyse the ester and hydrogen bonds between uronic acid groups of hemicellulose and cellulose with lignin (Van Soest 1982). The result can be seen by changes in infra red absorbance properties (Barton 1986). Evidence of the bonds' response can be shown by the decrease of p-coumaric and ferulic acids upon ammoniation of cereal straws. These compounds are linked with arabinose moieties of hemicellulose via the carboxyl groups (Mason et al. 1988). The bonds were identified by Mueller-Harvey et al. (1986) as O - [5-O-(trans-p-coumaroyl)- $\alpha$ -L-arabinofuranosyl] -(1 $\rightarrow$ 3)-O- $\beta$ -D-xylopyranosyl-(1 $\rightarrow$ 4)-D-xylopyranose and O-[5-O-(trans-feruloyl)- $\alpha$ -L-arabinofuranosyl]-(1 $\rightarrow$ 3)- O- $\beta$ -D-xylopyranosyl-(1 $\rightarrow$ 4)-D-xylopyranose.

Another important effect of NH<sub>3</sub> might be that disruption of the waxy surface layers of the straw eases the attachment of microorganisms (Tenrud et al. 1988). A high moisture level in straw during ammoniation helps solubilization of hemicellulose. Hemicellulose is a readily available substrate that can be used by rumen microorganisms. As a result increases in dry matter and fiber digestibility can be expected.

## Methods of Application

Stack method. Usually straw is ammoniated in stacks covered with plastic sheeting. There are no specific requirements regarding the shape and size of these stacks. However, it is suggested that the layers of straw bales be arranged at right angles to each other to obtain the best possible binding of the stacks. A lath should be placed in the middle of the stack to provide an entrance for the injection pipe. It is also important to adjust the amount of material in the stack to the size of plastic sheeting in order to ease the sealing of the stack.

Ammonia is usually transported in pressurized tanks and injected into the stack through a perforated metal pipe. Immediately after withdrawal of the injection pipe from the stack the hole should be taped properly in order to prevent ammonia leakage. Depending on ambient temperature, it takes 4 to 8 weeks to complete the reaction. In countries with warm weather this time could be reduced. The stack should be allowed to air at least two days upon opening to allow excess ammonia to disappear before feeding the straw. Ammonia is a potentially dangerous and toxic chemical. Stringent safety precautions need to be observed when using this material. For more detail of the stack method see Sundstol et al. (1978). There may be variations of the stack method. Ammoniation

can also be done in large round bales individually wrapped in plastic sheeting.

Oven method. This method was originally developed to reduce time of treatment at sites having low ambient temperatures. Instead of injecting ammonia gas, hot ammonia is circulated through straw in a sealed chamber. The length of treatment may take less than 24 hours. The oven works on a 23 hour cycle broken into three main processes: 15 hours of thermostatically controlled heating to 95° C, 4 hours of reaction, and 4 hours of ventilation (Tembo 1987). This work can be automated so that the manual work is mainly loading and unloading of the oven. The disadvantage of this method is that the cost of the equipment is relatively high.

Urea-hydrolysis method. Ammonia is easy to handle in the form of urea. At the farm scale, urea is diluted with water and sprayed onto the straw. If the straw is dry it can be mixed with equal weight of water containing 5% urea. Requirements for plastic or containers to seal the straw can be replaced with cheaper and locally available materials in developing countries. In one experiment conducted in Bangladesh, rice straw is ensiled with a urea solution either in earthen pits or bamboo bags, with inside

walls and top sealed with banana leaves (Dolberg et al. 1981). Time is required to allow an enzyme, urease, to breakdown urea into ammonia. In the case that straw does not contain ureolytic bacteria, sources of urease such as jackbean meal or soybean meal have to be added. Potential danger to animals exists when treated straw is fed and the urea breakdown has not finished. High levels of urea remaining in straw may cause urea toxicity. A three week reaction time is recommended when treating straw with urea (Sundstol and Coxworth 1984).

#### Factors Influencing the Effect of Ammonia Treatment

A number of factors influence the effect of ammonia treatment to straw. Amount of ammonia applied is the first factor. Generally, a 3.0 to 4.0% (wt/wt, DM basis),  $\text{NH}_3$  application is accepted as optimum (Kernan and Spurr 1978). Increasing the level of ammonia applied may have some beneficial effects but can not be justified when exceeding 4.0 %, DM basis (Sundstol et al. 1979). Lower levels of ammonia may not be able to prevent the growth of mold in the stack method.

Ambient temperature also plays a significant role in the reaction between straw and ammonia molecules. Temperature dictates the length of reaction time. Normally, the higher the temperature the shorter time required to

complete the reaction. Alibes et al. (1984) reported that N content and the digestibility of straw is higher when treatment is done in summer (38° C) than when done in winter (7° C). Increasing reaction time seems to be necessary at low ambient temperatures (Sundstol et al. 1978).

Moisture content is another important factor determining the effect of ammonia treatment. Experiments conducted by Sundstol et al. (1979) found no positive effect of anhydrous ammonia when straw had an extremely low moisture content (3.3%). Waiss et al. (1972) concluded that an optimal effect of ammonia treatment on the in vitro organic matter digestibility of rice straw is obtained at a moisture content of about 30 %. Increasing the moisture content of the straw from 12 to 50 % was found to have a positive effect on in vitro organic matter digestibility of oat straw treated with 5-7% NH<sub>3</sub> (Sundstol et al. 1979). Although there is no data that states a minimum moisture level for ammoniation, the effect of moisture is particularly clear regarding N retention in the straw after treatment. Dryden and Leng (1986) reported that at ammonia levels of greater than 4.5% straw dry matter, NH<sub>3</sub> could not be incorporated into air-dry straw (12% moisture). Reconstitution of dry straw prior to ammonia treatment probably will be advantageous.

The improvement of straw after treatment is also determined by the quality of starting material. The effect

of ammonia is generally more pronounced in material with a low digestibility. Horton (1981) found greater improvement in the digestibility of wheat straw than in barley and oat straw, although digestibility after treatment is highest for the latter two cereal straws. Similar results were reported by Kiangi et al. (1981) when treating maize stover, wheat straw and rice straw. Rice straw, which has the lowest initial digestibility, had the greatest increase of in vitro dry matter digestibility.

#### Advantages and Disadvantages of Ammonia Treatment

Whether ammonia treatment will be used widely as a means to improve nutritive value of straw depends on many constraints. It has to meet nutritional and economical demands and requires skilled personnel.

Treatment of cereal straw with ammonia usually results in increases of the metabolizable energy value and intake by animals. Ammonia also adds nitrogen to the material which can be utilized by rumen microorganisms for protein synthesis. At a practical level of application ammonia is a more effective preservative than NaOH, and there are no problems associated with the excretion of sodium by animals. Nevertheless, ammoniation is not a perfect technique for improving the feeding value of cereal straw. Only a part of the ammonia is actually recovered in the



material after treatment. Two thirds of ammonia applied may be lost. Compared with NaOH treatment, the improvement in energy yield from ammoniation is lower. Problems of air pollution still exists when treatment is done in a closed building. Care must be taken in handling anhydrous or aqueous ammonia.

### Nutritional Value of Ammoniated Straw

#### Crude Protein

The most significant effect of ammoniation is an elevated crude protein (CP) content for straw following treatment. A doubling of CP content is commonly found (Herrera-Saldana et al. 1982; Jewell and Campling 1986). Saenger et al. (1983) and Mason et al. (1988) reported a three fold increase in CP content of barley, wheat and oats straw after ammoniation. Dryden and Leng (1986) summarized 34 reports on the CP content of ammoniated straw. They found the CP range was  $93.75 \pm 29.37$  g/kg DM.

The increase in CP content of ammoniated straw is related to ammonia ( $\text{NH}_3$ ) retained after treatment. Dryden and Leng (1986) suggested that the amount of ammonia retained after treatment was between 20 and 40%. Gordon and Chesson (1983) divided the nitrogen (N) in ammoniated straw

into three fractions: i) water soluble-NH<sub>3</sub>-N, ii) water soluble non-NH<sub>3</sub>-N, and iii) water insoluble non-NH<sub>3</sub>-N. The water soluble NH<sub>3</sub>-N is unstable. The major reduction in N content after opening of the stack occurs in this fraction. Herrera-Saldana et al. (1982) reported that after four months storage 38% of N initially bound with straw is lost. Increased moisture levels in straw enhance the binding of NH<sub>3</sub> and straw resulting in higher CP content (Waiss et al. 1972, Hartley and Jones 1978). The major increase of CP content is probably in NH<sub>3</sub>-N form. Dryden and Kempton (1983) reported that most of the added N is in the water soluble fraction (67.4%) and 65.2% of this is NH<sub>3</sub>-N, and 34.6% is retained as water soluble non-NH<sub>3</sub>-N. Cell wall N contributes 11.5% of the total N. The 21.1% added N which is not identified was soluble in neutral detergent, but not in water. The N retained in cell wall, presumably, is bound to lignin.

Results for digestibility of protein are somewhat conflicting. Increased digestibility of straw protein following ammoniation was reported by Horton (1979), Herrera-Saldana et al. (1982) and Zorilla-Rios et al. (1989). Dias-da-Silva and Sundstol (1986) reported an increase from 16.5 to 42.0% and 38.2% in apparent digestibility of N after treatment with anhydrous ammonia and urea, respectively. Mandell et al. (1988), meanwhile, reported no increase in CP digestibility for barley straw ammoniated at various moisture levels. Sundstol and Coxworth (1984)

proposed that the utilization of ammonia added to straw depended on a number of factors such as: total amount of N in the straw, speed at which the N in straw is released in the gastro intestinal tract, amount of available energy (carbohydrate) in the rumen and degradability of dietary protein. In other words the ammonia might be considered as an ordinary source of non protein nitrogen (NPN).

Decrease of apparent CP digestibility has also been reported (Smith et al. 1984 and Zorilla-Rios et al. 1989). Horton et al.(1982) evaluated the effect of combined ammoniation and physical treatment on straw N utilization. Shredded or pelleted, nonammoniated or ammoniated barley straw were offered as 40 % of the diet DM. The remainder of the diet DM was supplied by barley grain and rapeseed meal. Urea was added to both the ammoniated and nonammoniated straw diet to obtain an 11.0% CP content of overall diet. The apparent digestibility of CP of shredded and pelleted straw were reduced from 69.3% to 67.2% and from 71.3% to 62.9% by ammoniation, respectively. There was no explanation of the cause of this reduction.

Mason et al. cited by Zorilla-Rios et al.(1989) concluded that a decrease in the apparent digestibility of N associated with a large intake of fibrous material, could be explained either by impaired reabsorption of endogenous N or by increased fecal output of nitrogenous compounds from ruminal and/or cecal bacteria. Furthermore, Thomas and Rook (1981) suggested that reduced ruminal digestion of

fiber due to high levels of dietary concentrate, could be compensated for by increased digestion in the lower gut. This would shift sites of digestion towards the lower tract and increase loss of microbial N in feces. Borhami and Johnsen (1981) reported that the duodenal flow of N from ammoniated straw was higher while the amount absorbed in the intestine was the same, resulting in more N excreted in the feces. It was suggested that a portion of  $\text{NH}_3$  is tightly bound to the straw and was not released during passage through the lower alimentary tract.

### Fiber

Most experiments showed that ammoniation decreases neutral detergent fiber (NDF) and hemicellulose content of straw, while responses for acid detergent fiber (ADF), cellulose and lignin content are not consistent. Zorilla-Rios et al. (1989) reported a decrease of NDF content from 80.7% to 69.9% and an increase of ADF content from 56.4 to 57.0% in wheat straw after ammoniation. A slight increase of cellulose and marked decrease of hemicellulose (54%) contents were reported by Streeter and Horn (1984) in ammoniated high moisture wheat straw. These trends were also observed in ammoniated wheat, barley and oats straws by Givens et al. (1988). Increasing levels of moisture content before ammoniation has been reported to increase

ADF content of wheat straw (Mandell et al. 1988). This increase could be due to the formation of Maillard reaction which is facilitated by moisture levels above 30% and a constant exposure to heat in the straw stack (Van Soest 1982).

Generally, the digestibility of fiber fractions in straw are increased by ammoniation. Williams (1984) reported an increased of ADF digestibility of barley straw from 47.0 to 59.0%. However, he also noted that the digestibility decreased with increasing level of barley grain supplementation. Although reconstitution of wheat straw prior to ammoniation increases straw ADF content it did not decrease digestibility of the ADF (Mandell et al. 1988). The digestibility of NDF in the same material increased by 10 %. Similar increases in NDF digestibility have been reported by Horton (1981) and Coxworth et al. (1981).

Dias-da-Silva and Sundstol (1986) observed increases of wheat straw cellulose and hemicellulose digestibility from 47.3 to 56.8% and from 56.4 to 71.2%, respectively. The results of ammoniation on digestibility of lignin are not consistent. Dias-da-Silva and Sundstol (1986) and Mandell et al.(1988) showed lowered digestibility, while Herrera-Saldana et al.(1983) reported an improved lignin digestibility due to ammonia treatment.

Ammoniation also influences the recovery and composition of straw cell walls. Mason et al. (1988)

reported that between 8.0 and 9.0% of the walls of untreated straw are rendered soluble in neutral detergent solution by the ammonia treatment, producing proportionate increases in cellulose and lignin relative to hemicellulose. Reconstitution with water has also been reported to increase solubilization of straw hemicellulose exposed to alkali treatment (Streeter and Horn 1984; Mandell et al. 1988).

#### Dry Matter and Organic Matter

Ammoniation of straw usually results in increased in vivo and in vitro dry matter and organic matter digestibility. Dryden and Kempton (1983) showed substantial increases for in vivo organic matter and cell wall organic matter apparent digestibility of barley straw after ammoniation. These values were measured directly and were not due to N supplementation. The increases were 42.0% for organic matter and 39.0% for cell wall organic matter digestibility. When urea is supplemented to untreated straw at a level equivalent to the amount of water soluble N retained after ammoniation no significant increase of digestibility is observed. Increased in vitro digestibility of dry matter has also been reported by Zorilla-Rios et al. (1985). They found that in vitro organic matter digestibility of wheat straw increases from 37.3 to 47.6%

after ammoniation.

Givens et al. (1988) conducted digestibility studies in wheat, barley and oat straw. They found that the mean increases in digestible organic matter, coefficient of organic matter digestibility, digestible energy and metabolizable energy content in vivo were: 97.9 g/kg, 0.10, 1.4 MJ/kg DM and 1.2 MJ/kg DM; respectively. Oat straw was upgraded to a lesser extent relative to wheat and barley straws.

### Feed Intake

Since straw has a low digestibility, voluntary intake plays a major role in determining animal productivity. Intake of low quality roughages depends largely on the rate at which the roughage dry matter leaves the rumen (Dryden and Kempton 1983). Therefore, increasing both the rate and extent of digestion in the rumen will result in an increased intake of digestible nutrients.

Dryden and Kempton (1983) have observed that sheep ate 79.0% more digestible organic matter per unit metabolic body weight when fed ammoniated barley straw compared with untreated straw. The increase of straw digestibility has also been reported to cause an 80% increase in digestible dry matter consumption by heifers (Orskov et al. 1983). Both authors found that adding urea to untreated straw did

not increase dry matter intake. A significant increase of straw dry matter intake after ammoniation was reported by Saenger et al. (1983), Streeter and Horn (1984) and Zorrilla-Rios et al. (1985). While Mandell et al (1988) did not find a significant increase in straw intake.

When straw is ammoniated its physical characteristics change. An increase in fragility of wheat straw after ammoniation was reported by Zorrilla-Rios et al. (1985). Fragility of straw is estimated by the amount of dry matter that passes through a 1 mm sieve after 20 seconds of grinding and 10 minutes of sieving. Ammoniation increased straw fragility from 58 to 67.8 units. Saenger et al. (1982) also observed that corn stover is less coarse and more pliable when ammoniated.

Increased fragility is speculated to increase the rate of breakdown of ingested particles during chewing and rumination and to increase the rumen pool of small particles (Zorrilla-Rios et al. 1985). This would have a positive effect on intake if the particles are cleared at a faster rate by digestion and the undigested material leaves rumen in much shorter time. However, Dryden and Kempton (1983) observed that ammoniation does not increase the ruminal digestion rate. They suggested that the increase of intake by sheep fed ammoniated straw must be due primarily to the increase in the extent of straw digestion.

A decrease of straw intake is possible if concentrate is supplemented in the diet. Horton (1979) reported that



straw consumption per unit of metabolic weight is reduced by 24 % when concentrate is offered as 43 % of the ration DM, compared to straw fed alone. However, light supplementation of treated wheat straw with corn grain showed significantly higher intake by yearling steers than untreated straw supplemented with soybean meal (Saenger et al. 1983).

### Performance

Horton (1979) reported that cereal straw had been used extensively for wintering beef cattle in Western Canada. Most feeding trials with ammoniated straw used protein and energy supplements to balance the ration. The use of ammoniated straw as the sole dietary ingredient for Friesian heifers has been reported by Orskov et al. (1983). Over seven weeks heifers receiving ammoniated barley straw gained 324 g/d, while heifers receiving untreated straw lost 447 g/d. The superiority of ammoniated straw over untreated straw was also reported by Saenger et al. (1983). This, partially, can be explained by an increase of digestible dry matter intake for animals consuming ammoniated straw.

More recently, Silva et al. (1989) conducted an experiment using ammoniated or nonammoniated straw as the basal diet in sheep, steers and bulls. Results showed that

all animals given treated straw gained weight while animals given nonammoniated straw lost weight. Diets based on ammoniated straw promoted growth in all animals. However, the body weight gain achieved by cattle with untreated straw supplemented with 50 g/kg DM fish meal or 150 g/kg DM sugar beet pulp were greater than those when ammoniated straw was given as the sole feed. When the same supplements were combined with ammoniated straw the animals gained almost twice as much as those animals receiving nonammoniated straw as a basal diet.

Effect of ammoniation on milk yield of dairy cows has also been observed by Orskov et al. (1988). The barley straws used in this study had different degradabilities, namely Corgi (higher degradability) and Gerbel (lower degradability). The untreated and ammoniated straws were offered to cows at a level of 50 % of the dietary DM. Milk yield of the animals receiving the diet based on treated Corgi was significantly higher (5 kg/d) than that of other diets. Liveweight loss was greatest for the cows receiving the diet based on untreated Gerbel.

Based on the information shown above, it seems that ammoniated straw has a great potential use as a maintenance diet. For maximal production, an appropriate supplement needs to be included. The value of ammoniated straw, of course, will also be determined by factors such as price, availability and quality of the both straw and supplement; and physiological status of the animals.

## Rumen Degradation of Straw

### Colonization and Digestion of Straw Cell Wall by Rumen Bacteria

The existence of rumen microorganisms is vital in ruminants fed low quality roughage. The host animal energy requirement is supplied by absorption of the end products of cell wall digestion by microorganisms. Therefore, strategy of feeding straw should be directed toward maximizing metabolizable energy consumption and microbial protein synthesis.

Straw entering the rumen is subject to rapid and extensive colonization by microorganisms. There is evidence that colonizing microorganisms have preferences to cut end and damaged areas of ingested feed (Cheng et al. 1981), although all surfaces are potentially available for attack. The major cellulolytic rumen bacteria closely associated with the surface of plant particles are Bacteroides succinogenes and Ruminococcus flavefacien (Cheng et al. 1984). Bacteria adhere strongly by means of an extension to their glycocalyx. Most of bacteria adhere to and digest the un lignified walls of the innermost layer of parenchyma.

Chesson and Orskov (1984) suggested that adhesion of microbes and their enzymes was probably to the substrate itself, which must be located at the plant cell surface. As available substrate is degraded, material unable to act as

a substrate for microbial enzymes or as a binding site for the organisms themselves becomes exposed and would be expected to accumulate. In straw, lignin is probably the material that will accumulate during digestion and protect the surface from further digestion after a relatively small amount of soluble carbohydrates has been digested.

Russel et al. (1988) examined spectra of rumen incubated straw using multiple internal reflectance infrared spectroscopy of wheat and barley straw. They found that no degradation occurred at the outer surface but appreciable polysaccharides had been solubilized from the inner surface after 120 hours of digestion. While lignin and acetyl groups were found at much higher levels at the inner surface, suggesting that concentration of this compound maybe a limiting factor in the progress of the degradation of straw. Chesson cited by Russel et al. (1988) proposed that rumen microorganism attack on plant cell wall is preceded by a preferential degradation of polysaccharide exposed at the surface of cell walls leaving phenolic components of the wall virtually unmodified. Observations on alkali treated straw showed that alkali treatment scarcely alter the chemistry of inner surface but significantly modifies that of the outer layer. Modification includes hydrolysis of cutin and acetyl ester groups, dissociation of a large proportion of the silica, and partial degradation and solubilization of lignin. It suggests that microorganism attack of alkali treated straw

could proceed at both the inner and outer surfaces as a result of these chemical changes to the cell wall component. This theory is not verified since residue from rumen digestion of alkali treated straws is highly fragmented and it is impossible to distinguish the inner and outer surfaces.

### Extent and Rate of Digestion

Several factors influence the rumen degradability of feedstuffs. Straw based diets are low in soluble carbohydrates, therefore, only a small amount of substrate is available to meet the immediate needs of invading rumen microorganisms. Consequently, the attachment and subsequent colonization of rumen bacteria takes some time. This creates a lag phase, during which little or no digestion takes place. Some rumen microbes are capable of utilizing N in the form of ammonia to synthesize protein (Smith 1969). Logically, feeding ammoniated straw could provide the ammonia needed. However, certain amino acids are also required by rumen microorganisms. Huque and Thomsen (1984) reported that the in vitro digestibility of cellulose was greater with soybean and casein as substrates for rumen microbes than with urea.

The speed at which the digestible components are removed from a feedstuff is important also. It determines

the length of time that feed particles occupy the rumen and availability of space for the incoming feedstuffs. To enable the animal to maintain a high turnover rate of straw the rate of degradation should be maximized (Chesson and Orskov 1984).

Another important factor influencing the rumen degradability of feedstuff is the extent of digestion. This is the characteristic of feed which is most often known. It is normally taken to be equal to the value obtained from a digestibility determination (Chesson and Orskov 1984).

A method to describe the rate and extent of digestion was suggested by Orskov and Mc Donald (1979). They found that the disappearance of substrate from nylon bags incubated in the rumen could be calculated by the equation:  $p = a + b (1 - e^{-ct})$ , where  $a$  is the rapidly soluble material which is immediately degraded,  $b$  is the fraction that will be degraded in a given time,  $c$  is the rate constant for digestion of  $b$ ,  $p$  is the amount degraded at time  $t$  and  $(a + b)$  is the potential extent of digestion.

Because of the intimate contact of feed particles with ruminal microflora, there is possible contamination of microbia in the residue of feedstuff after incubation. This will contribute error in estimating true nutrient digestibility, especially nitrogen, of feed by the nylon bags technique (Nocek 1988). Correction should be made for eliminating the effect of microbial contamination, such as using diaminophimmelic acid (DAPA) analysis. Varkiko and

Lindberg (1985) reported that the effect of correction for bacterial nitrogen contamination on error associated with determination of residual nitrogen in barley straw at 5, 12 and 24 hours of incubation were 164.5, 146.3 and 204.6%, respectively.

#### Effect of Ammoniation on Straw Degradability

Generally, ammoniation increases the overall degradability of straw in the rumen. Morrison and Brice (1984) found that ammonia treated barley straw had a shorter lag phase than untreated straw. By 24 hours only about 1% of untreated straw fiber DM was digested while more than 8% of the DM was removed from the ammonia treated straw. They suspected that the difference might have been due to the lower content of acetyl groups in treated straw. Treated straw contained only about 25 % of the bound acetyl groups found in untreated straw. However, there was no evidence that lignin was digested. The overall digestibility of DM increased from 31.5 to 46.1 %. These numbers are low compared to results observed by Fahmy and Orskov (1984) who found that ammoniation increased 48 hour incubation from 48 to 61.9 % and from 45.9 to 60.3 % for dry matter and organic matter disappearance, respectively.

The rate of disappearance of straw in the rumen is not usually altered by ammoniation (Dryden and Kempton

1983; Morrison and Brice 1984). Adebowale et al (1989) reported that ammoniation increased potential degradability of wheat straw and maize stover from 59.9 % to 72.2% and from 67.7% to 74.1%, respectively. Dryden and Kempton (1983) found ammoniation increased potential digestibility of barley straw 23 % for dry matter and 29% for cell wall organic matter. Tuah et al. (1986) reported that the dry matter loss of ammoniated barley straw incubated in nylon bags suspended in rumen of sheep was greater for varieties with initially low digestibility than those of higher digestibility.



## Experiment I

### Effect of Reconstitution and Ammoniation on Intake and Nutritive Value of Barley Straw

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straw.

Key words : ammoniation, reconstitution, digestibility,  
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straw.

## ABSTRACT

The effect of moisture level on ammoniation of barley straw was investigated using four crossbred Suffolk lambs in a 4x4 intake, digestion and nitrogen balance latin square trial. Animals were fed nonammoniated straw containing 13% moisture (NA), ammoniated straw containing 13 % moisture (DA), and ammoniated straw reconstituted to 27% (RA-27) or 37% (RA-37) moisture. Straw made up 76.2 % of dietary dry matter intake, the remainder supplied by barley grain. Urea ( $10.4 \text{ g kg}^{-1}$  dry matter complete feed) was added in the grain for animals consuming NA. Dry matter digestibility of straw was increased ( $P < 0.05$ ) with treatment RA-27 only. Digestibility of NDF, ADF and hemicellulose were influenced ( $P < 0.05$ ) by ammoniation and reconstitution, values for total diet being 55.6, 50.2 and 65.4 % (NA); 57.0, 51.2, 67.6 % (DA); 64.7, 57.5, 78.5 % (RA-27) and 59.9, 52.4, 76.9 % (RA-37), respectively. While nitrogen balance did not differ among treatments, the digestibility of total diet crude protein (CP) was influenced ( $P < 0.01$ ) by ammoniation and reconstitution, values being 59.4, 48.7, 44.6 and 39.1 % for NA, DA, RA-27 and RA-37, respectively. No difference ( $P > 0.05$ ) on straw intake was observed. Results indicated that reconstitution of barley straw prior to ammoniation may increase digestibility of the fiber fraction, however, this process reduced the availability of straw protein for the lambs.

Straw samples used in the lamb trial were incubated in the rumen of three mature steers using the nylon bag technique. Samples were withdrawn at 0, 2, 4, 6, 12, 24 and 48 hours post incubation. Results indicated that ammoniation and reconstitution at 37% moisture increased the degradation of rapidly soluble DM and ADF from rumen ( $P < 0.05$ ). Potential degradability of DM was increased by reconstitution and ammoniation ( $P < 0.05$ ). Ammoniation alone did not affect straw's degradability ( $P > 0.05$ ). The rate of degradation was not influenced by straw treatments ( $P > 0.05$ ).

## INTRODUCTION

Intense pressure on land use for human food production in developing countries has increased use of agricultural byproducts such as cereal straw by ruminants. Meanwhile, surpluses of cereal straw in some developed countries have been reported to lead to burning as a method of straw disposal, a practise condemned for environmental reasons.

Inherently, straws are low in metabolizable energy and contain negligible amounts of protein, minerals and vitamins. A number of chemical treatments have been developed to improve straw utilization by ruminants. Ammoniation is a well established technique used to improve the nutritive value of these low quality roughages. Various factors affect the efficiency of ammoniation (Sundstol et al. 1978). The amount of ammonia ( $\text{NH}_3$ ) retained in the straw after treatment is related to the water content prior to ammoniation. The presence of water provides greater contact between the  $\text{NH}_3$  molecule and the plant cell wall. Mandell et al. (1988) reported increases in crude protein content and digestibilities of hemicellulose and cellulose for wheat straw ammoniated at 30% moisture. However, data relating to changes in protein digestibility of straw due to reconstitution and ammoniation is limited and not consistent (Horton 1979; Dias-da-Silva and Sundstol 1986; Zorrilla-Rios et al 1989).

The first trial of this experiment was conducted to

evaluate the effect of moisture level prior to ammoniation of barley straw on intake, digestibility and nitrogen balance in lambs. The second trial was conducted to examine rumen degradation of these straws.

## MATERIALS AND METHODS

### Ammoniation of straw.

One hundred square bales of barley straw, 13% moisture, obtained from one field were separated into four groups. One group was untreated (NA). The remaining three groups were ammoniated at 3 % (wt/wt, dry matter basis) without reconstitution (DA) and after reconstitution to reach moisture levels of 27 % (RA-27) or 37 % (RA-37). Reconstitution was done on an individual bale basis. The correct moisture content was obtained by weighing each bale before and during reconstitution. Following reconstitution, bales were stacked, covered with 35  $\mu$ m black plastic polyethylene and injected with anhydrous ammonia according to Sundstol et al.(1978).

Stack temperatures were recorded twice daily using silicon coated thermocouple wires. Twenty eight days following ammoniation, stacks were opened and the straws were chopped with a forage harvester. The were allowed to air 4 days before they were fed to lambs.

### Intake, digestibility and N-balance trial

Four crossbred Suffolk lambs, with an average initial

body weight of  $27.1 \pm 0.5$  kg and age of 82 d, were assigned to a 4 x 4 latin square trial. Animals were housed in individual metabolism crates with free access to water. Diets were formulated to meet the energy requirement for maintenance (National Research Council 1985). Four treatments, consisting of non ammoniated (NA) and ammoniated straw (DA, RA-27 and RA-37) were fed along with a barley grain mix throughout four periods (appendix 2). Straw was fed twice daily at 10:00 and 16:00 hr at 76.2% of the dietary dry matter (DM) intake. The barley grain mix was offered over a 24 hr period using a continuous feeder. For animals consuming treatment NA, urea (10.4 g kg<sup>-1</sup> DM of complete diet) was added in the diet. The urea was mixed with the grain through dilution with water.

Each period consisted of: 10 days adaptation to the diet, 7 days voluntary intake measurement, 3 days adjustment to 90% of voluntary intake and 6 days digestibility and nitrogen balance (Heaney et al. 1969). During the adjustment and intake period, the amount of straw offered daily was such that a 10% weigh back was left. The amount of grain offered daily was based on the amount of straw (DM basis) consumed on the previous day.

Straw, grain mix and weigh back samples were taken daily during the intake and digestibility trials and stored (-20° C) for further analysis. During the nitrogen balance phase, 25 ml of 10 N sulfuric acid was added in the urine receiver. Fecal samples were collected twice daily at

10:30 and 16:30 hr using fecal collection bags. Feed samples and a 10% aliquot of fecal and urine samples were stored (-20° C) immediately after collection.

At the end of each period, rumen liquor samples were taken via an esophageal tube attached to a strained metal bolus (Ingalls et al. 1980). The rumen liquor pH was measured immediately using a digital pH wand (Cole-Parmer's 5985-50, Cole-Parmer Instrument Co.). After centrifugation (2000 rpm, 15 minutes), supernatant of rumen liquor was taken for volatile fatty acid (VFA) analysis according to Erwin et al. (1961). A blood sample was taken from the jugular vein using a vacutainer for blood urea analysis. Blood urea nitrogen was determined by autoanalyser procedure according to Marsh et al. (1965).

Straw and fecal samples were dried with a freeze drier and ground to pass through a 1 mm screen. Feed and feces DM, CP and total ash were determined according to Association of Official Analytical Chemists (AOAC 1980). Neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid insoluble nitrogen (ADI-N) were determined according to Goering and Van Soest (1970). Hemicellulose content was calculated as the difference between NDF and ADF. In addition, fungal invasion for each straw treatment was measured through its hydrolysis product, glucosamine, as described by Wittenberg et al. (1989). Apparent digestibility of barley straw alone was calculated by difference, using a barley grain digestibility value of



78.0% for DM (Orskov et al. 1974) and 77.60% for CP (Oltjen et al. 1967).

### **Nylon bag trial**

Samples of straw fed to lambs in period I and IV of the previous trial were taken for determination of DM, CP, NDF and ADF rumen disappearance using three rumen cannulated steers (Orskov and McDonald 1979). Steers were fed 9.6 kg DM to provide one and half times their nutrient requirements for maintenance (National Research council 1984) with a 10% barley grain, 20% untreated straw and 70% grass-alfalfa diet (Appendix 13).

Approximately 5 g of the straw samples (DM) were placed into nylon bags measuring 15 cm x 11 cm with pore size of  $50 \pm 2$  micron. Bags were placed into a weighted laundry bag measuring 30 cm x 30 cm and pore size of 2 mm x 3 mm. Samples were incubated in the rumen for 0, 2, 4, 6, 12, 24 and 48 hr. All bags were removed at the same time, except for 0 hr where samples were incubated in the rumen for 5 minutes after all of the other samples had been removed from the rumen. Immediately, the bags were washed in water ( $4^{\circ}$  C, 10) minutes and dried in a forced air oven ( $55^{\circ}$  C).

Dry matter, CP, NDF and ADF disappearances were determined. Diaminophimelic acid (DAPA) content of straw

residue was analysed to correct for microbial contamination according to Hutton et al.(1971). The kinetics of degradation was estimated from the following first order equation (Orskov and McDonald 1979):

$$p = a + b ( 1 - e^{-ct} ) \quad \text{equation 1}$$

where:

$p$  = the amount of degraded material at time  $t$  (%),

$a$  = the rapidly soluble material (%),

$b$  = fraction that will be degraded in a given time  
(%),

$e$  = 2.71828,

$c$  = the rate constant for degradation of  $b$ ,

$t$  = time of incubation (hr),

$a+b$  = potential degradable fraction (%),

All statistical analysis was performed using General Linear Model (GLM) procedure, except for nylon bag trial which used Non Linear Model (NLM) (Statistical Analysis System Institute Inc. 1986). Means comparisons were done using Duncan and Least Square Means Procedure for the lamb trial and the nylon bag trial, respectively.

## RESULTS AND DISCUSSION

### Temperature of stacks and mold growth

Temperatures of individual bales within straw stacks subjected to the various treatments did differ ( $P < 0.01$ , table 3). Reconstitution increased temperature of the stacks during storage. Peaks of treatment RA-27 and RA-37 were achieved at the second day after treatment, with maximum values of 37.2 and 41.8° C (figure 1).

Upon opening stacks, visible molding of the straw was observed in reconstituted stacks. Fungal invasion was characterized by white powder of fungus, which was more obvious in the 37% moisture level of straw (RA-37) than the other stacks. A quantitative assessment for fungal invasion from samples taken upon opening stacks and in each period of the digestion trial (table 3) showed that the concentration of glucosamine, the hydrolysis product of spores and mycelium of fungi, was highest ( $P < 0.05$ ) in treatment RA-37. This fungal invasion appears to have been facilitated by the abundance of water in the stack.

### Chemical composition.

Results from chemical analysis showed that ammoniation increased the CP content of the straw ( $P < 0.01$ , table 3).

Figure 1. Effect of reconstitution on temperature ( $^{\circ}$  C) of barley straw the first ten days after ammoniation (n=2).

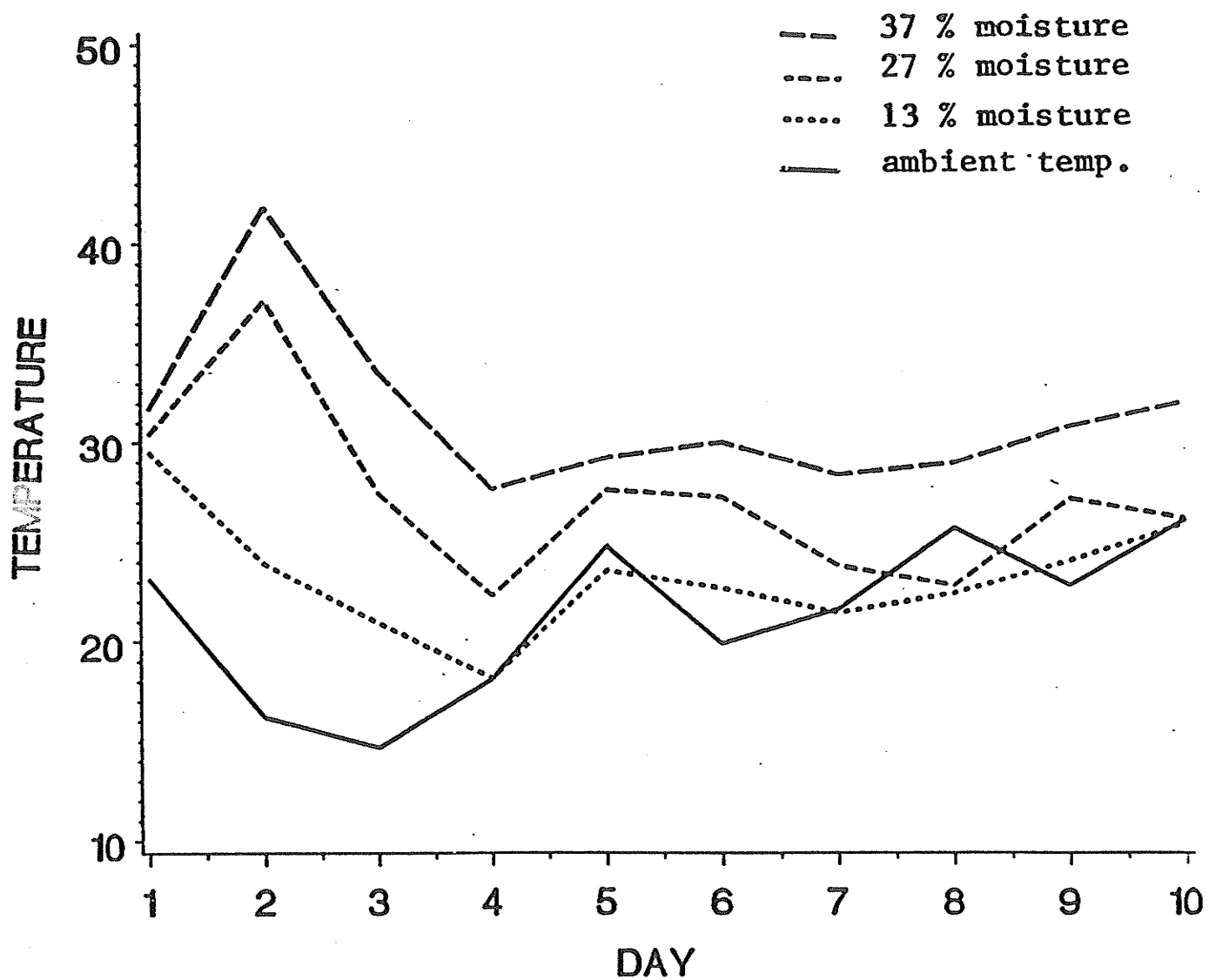


Table 3. Effect of ammoniation and reconstitution of barley straw on chemical composition (DM basis, n=4) and stack temperature (n=20).

Item	Treatment				SE
	NA	DA	RA-27	RA-37	
CP, %	5.2 <sup>b</sup>	6.8 <sup>a</sup>	7.7 <sup>a</sup>	7.5 <sup>a</sup>	0.3
NDF, %	80.7	79.7	79.2	77.1	1.1
ADF, %	54.3 <sup>b</sup>	54.6 <sup>b</sup>	55.2 <sup>ab</sup>	56.8 <sup>a</sup>	0.5
ADIN, %	0.14 <sup>c</sup>	0.17 <sup>bc</sup>	0.20 <sup>b</sup>	0.25 <sup>a</sup>	0.01
Hemicellulose,					
%	26.4 <sup>a</sup>	25.2 <sup>ab</sup>	23.9 <sup>b</sup>	20.3 <sup>c</sup>	0.6
Ash (%)	6.4	6.0	6.8	7.7	0.5
Glucosamine,					
mg g <sup>-1</sup>	3.37 <sup>b</sup>	3.94 <sup>b</sup>	3.91 <sup>b</sup>	6.77 <sup>a</sup>	0.68
Stack temperature <sup>¶</sup>					
°C	21.3 <sup>c</sup>	23.3 <sup>c</sup>	27.2 <sup>b</sup>	31.4 <sup>a</sup>	1.2

a,b,c Means in the same row bearing different superscripts differ (P<0.05).

<sup>¶</sup> mean stack temperature during the first 10 days following ammoniation.

However, reconstitution did not markedly increase the amount of nitrogen retained in the straw after ammoniation when compared with dry straw ( $P>0.05$ ). No difference in NDF concentration was observed among treatments ( $P>0.05$ ). While ADF increased ( $P<0.05$ ) due to a combination of reconstitution and ammoniation, the concentration of hemicellulose decreased ( $P<0.01$ ). The increase of ADF and decrease of hemicellulose in ammoniated and reconstituted straw have been previously reported (Mandell et al. 1988). Higher water concentrations could have increased the contact between  $\text{NH}_3$  molecules and straw cell wall, resulting in increased solubilization of hemicellulose of reconstituted straws. Mandell et al. (1988) suggested that increased ADF concentration could be due to Maillard reaction. Although, the temperature of the stacks did not reach  $60^\circ\text{C}$ ; moisture levels above 30% and constant heat exposure in the stack could have led to formation of Maillard reaction product (Van Soest 1982). It is interesting to note, that the concentration of ADI-N was increased with ammoniation and reconstitution ( $P<0.01$ ). This compound has been associated with heat damaged forage (Yu and Thomas 1976).

#### **Dry matter intake, digestibility and nitrogen balance.**

The proportion of straw to grain for all diets in this

experiment was kept the same throughout the trial. This was intended to eliminate differences in response due to any associative effect between straw and grain.

Several authors have reported increases in straw intake following ammoniation (Abidin and Kempton 1981; Streeter and Horn 1984). No differences in straw intake were observed among treatments when determined as DM consumed or as DM intake % body weight (BW) ( $P > 0.05$ , table 4). The intake response observed in this study may be related to the fact that animals received similar proportions of grain and similar dietary protein levels, although it was in the form of urea in treatment A.

Ammoniation affected dry matter digestibility for treatment RA-27 only ( $P < 0.05$ ). Reconstitution, prior to ammoniation increased the digestibility of NDF, ADF and hemicellulose in total diet ( $P < 0.01$ , table 4). Digestibilities were greatest in straw reconstituted to 27 % moisture. Van Soest et al. (1984) suggested that the cell wall of ammoniated straw, when under microbial attack, underwent a greater degree of particle disintegration. Results on fiber digestibilities in this trial showed that straw in treatment RA-27 and RA-37 behaved differently. Straw in treatment RA-37 could have undergone a further microbial related process, suggested by an elevated concentration of glucosamine, which may have reduced fiber digestibility.



Table 4. Effect of ammoniation and reconstitution of barley straw on DM intake and digestibility in growing lambs (DM basis, n=4).

Item	Treatment				SE
	NA	DA	RA-27	RA-37	
Intake,					
Total diet					
g DM d <sup>-1</sup>	740.2	790.6	873.4	837.8	40.5
Straw					
g DM d <sup>-1</sup>	564.3	601.4	666.1	636.8	36.8
% BW	1.92	2.07	2.28	2.27	0.11
Digestibility,					
Total diet					
DM, %	55.8 <sup>b</sup>	55.7 <sup>b</sup>	59.8 <sup>a</sup>	56.2 <sup>b</sup>	0.7
CP, %	59.4 <sup>a</sup>	48.7 <sup>b</sup>	44.6 <sup>c</sup>	39.1 <sup>d</sup>	1.0
NDF, %	55.6 <sup>c</sup>	57.0 <sup>bc</sup>	64.7 <sup>a</sup>	60.0 <sup>b</sup>	1.1
ADF, %	50.2 <sup>b</sup>	51.2 <sup>b</sup>	57.5 <sup>a</sup>	52.4 <sup>b</sup>	1.2
Hemicellulose,					
%	65.5 <sup>b</sup>	67.6 <sup>b</sup>	78.5 <sup>a</sup>	77.0 <sup>a</sup>	0.9
Straw					
DM, %	48.9 <sup>b</sup>	48.7 <sup>b</sup>	54.2 <sup>a</sup>	49.4 <sup>b</sup>	0.9
CP, %	13.0 <sup>b</sup>	29.9 <sup>a</sup>	26.8 <sup>a</sup>	17.0 <sup>ab</sup>	3.6

a, b, c, d Means in the same row bearing different superscripts differ (P<0.05).

The digestibility of CP in total diet was significantly decreased by ammoniation and reconstitution, while digestibility of CP in straw alone was increased ( $P < 0.05$ ) by ammoniation and a combination of reconstitution and ammoniation, except in treatment RA-37. Streeter and Horn (1984) reported that the majority of N in the straw ammoniated in the stack was present either as free  $\text{NH}_3\text{-N}$  (42.6%) or residual N (43.2%). A part of free  $\text{NH}_3\text{-N}$  might have been lost when straws were exposed to air. Thus, the portion of readily available N was reduced. On the other hand, the concentration of ADIN increased with ammoniation and reconstitution in this study. The presence of this compound was negatively correlated to N digestibility (Yu and Thomas 1976). The mechanism, however, is still not well understood.

Analysis on ADIN content of feces presented a significant difference among treatments ( $P < 0.05$ ) with order the reverse of the CP digestibility, ADIN values being 7.6, 9.1, 10.3 and 14.3 % of protein intake for animals consuming NA, DA, RA-27 and RA-37, respectively. However, when the ADIN content of straw and feces were accounted for, order of CP digestibility for straw treatment did not change.

Decreases in N digestibility of ammoniated straw has also been reported by Borhami and Johnsen (1981). They noted that the amount of N apparently absorbed in the intestine was low compared to the duodenal flow of N from

In the N balance trial it was found that animals consuming diet RA-27 and RA-37 excreted more N in the feces than animals consuming diet NA and DA ( $P < 0.05$ , table 5). In the contrary, animals consuming diet NA and DA proportionally excreted more N in the urine than animals consuming diet RA-27 and RA-37. Yet, the values of N balance and N retention did not differ ( $P > 0.05$ ). It indicates that addition of water reduces the digestibility of N after ammoniation. In the same time, the N absorbed from the gastro intestinal tract in animals consuming diet NA and DA was not well utilized. Whether it was supplied by urea in the grain mix or ammoniation of straw, the N utilization of all straw treatments was the same.

No difference was observed for the concentration of blood urea-N ( $P > 0.05$ , table 5). Animals consuming ammoniated and reconstituted straws tended to have low level of both blood urea-N ( $P < 0.11$ ) and urine-N ( $P < 0.05$ ). Lower levels of N in the urine generally is associated to low blood urea-N, which was true in these results. The average protein content of the diets in this trial was 9.1%. At low dietary intake of N, the recycling of urea should be more efficient (Van Soest 1982). These findings support the suggestion that a portion of ammonia was tightly bound to the straw and was not released during passage through lower alimentary tracts (Borhami and Johnsen 1981), therefore, reducing availability of straw protein for lambs.

Table 5. Effect of ammoniation and reconstitution of barley straw on N intake, N balance and blood urea-N in growing lambs (DM basis, n=4).

Item	Treatment				SE
	NA	DA	RA-27	RA-37	
N intake, g d <sup>-1</sup>	10.2	9.5	11.4	10.3	0.6
Fecal N output, g d <sup>-1</sup>	4.2 <sup>b</sup>	5.0 <sup>b</sup>	6.3 <sup>a</sup>	6.2 <sup>a</sup>	0.2
Urinary N output, g d <sup>-1</sup>	3.7 <sup>a</sup>	2.7 <sup>ab</sup>	2.8 <sup>ab</sup>	1.7 <sup>b</sup>	0.3
N retention, g d <sup>-1</sup>	2.3	1.8	2.2	2.3	0.3
N balance, %	21.8	18.7	19.3	22.3	2.7
Blood urea N, mg dl <sup>-1</sup>	6.6	5.3	4.9	3.6	0.7

a, b Means in the same row bearing different superscripts differ (P<0.05).

protein for lambs.

No differences on volatile fatty acids concentration and rumen pH among treatments were observed in this trial ( $P>0.05$ , table 6). It shows that source of N, as either urea or ammonia did not influence rumen fermentation of the straw based diets. The use of a value of 5.5% CP for ammoniated wheat straw, instead of 8.5 to 9.0% usually obtained from chemical analysis, was suggested by Males (1987) when formulating diets containing  $\text{NH}_3$ -treated wheat straw. Results from the lamb trial support this approach for barley straw as well.

#### Rumen degradation

Ammoniation alone did not significantly increase degradation of DM and fiber fractions ( $P>0.05$ , table 7). However, if accompanied with reconstitution at 37 % moisture it increased the rapidly soluble fraction (a) for DM and ADF ( $P<0.05$ ). There was no significant effect of treatment on the slowly degradable fraction (b) ( $P>0.05$ ). Effect of ammoniation and reconstitution of barley straw on its rate of degradation from rumen (c) was also not significant ( $P>0.05$ ). Meanwhile, the potentially digestible DM (a+b) of straw was increased by reconstitution and ammoniation ( $P<0.05$ ). Similar results have been reported by Dryden and Kempton (1983) and

Table 6. Effect of ammoniation and reconstitution on rumen pH and VFA concentration in growing lambs (n=4).

Item	Treatment				SE
	NA	DA	RA-27	RA-37	
Rumen pH	6.9	6.9	6.8	6.9	0.1
Acetate, mg dl <sup>-1</sup>	198.7	233.5	211.1	187.8	13.1
Propionate, mg dl <sup>-1</sup>	62.8	63.8	59.1	56.9	2.6
Isobutyrate, mg dl <sup>-1</sup>	4.6	4.8	4.3	3.6	0.2
Butyrate, mg dl <sup>-1</sup>	48.2	46.5	43.0	34.3	8.8
Isovalerate, mg dl <sup>-1</sup>	7.7	11.4	7.7	5.9	1.7
Valerate, mg dl <sup>-1</sup>	3.8	4.7	3.7	3.1	0.3
Total VFA, mg dl <sup>-1</sup>	325.7	364.7	328.8	291.7	21.6

Morrison and Brice (1984). This could in part answer why feed intake in the lamb trial was not significantly different although the potentially digestible DM has been increased by reconstitution and ammoniation. If increased digestibility were accompanied with increased rate of digestion a positive effect on DM intake could have been obtained. Ammoniation alone did not result in increased DM degradability ( $P>0.05$ ). There were no differences in potentially degradable NDF and ADF among treatments ( $P>0.05$ ).

An attempt to evaluate the characteristics of protein in ammoniated straw was not successful in this trial. In all treatments, the content of N in sample residue increased with time. It was necessary to correct the contamination caused by rumen microbial N by analysing the DAPA content of each sample. Since data on protein degradation did not fit to the equation used with the other components, no further statistical analysis was conducted (table 8). It was shown that ammoniated straw had greater protein degradability than non ammoniated straw. However, there was no obvious sign that degradability increased with time of incubation. Dryden and Kempton (1983) reported that ammoniated straw had two forms of N, water-soluble-N and cell wall-N. The first form accounted for 73.4% of the total pool N and was rapidly removed in the rumen. The second form accounted for 26.6% of the pool N and was essentially unavailable. Based on this data it is suggested

Table 7. Effect of ammoniation and reconstitution of barley straw on characteristics of DM, NDF and ADF rumen degradation.

Item	Treatment	Parameter <sup>¶</sup>			
		a	b	(a+b)	c
DM	NA	11.3 <sup>b</sup>	54.5	65.8 <sup>c</sup>	3.1
	DA	11.9 <sup>b</sup>	60.8	73.0 <sup>bc</sup>	2.9
	RA-27	12.9 <sup>b</sup>	66.2	79.1 <sup>ab</sup>	3.3
	RA-37	17.7 <sup>a</sup>	64.3	82.0 <sup>a</sup>	3.0
	SE	0.9	4.5	4.6	0.3
NDF	NA	7.3	63.1	70.4	3.0
	DA	8.4	68.9	79.0	2.7
	RA-27	5.3	77.8	81.7	3.2
	RA-37	4.9	71.0	77.4	3.2
	SE	1.0	1.6	2.1	0.0
ADF	NA	5.7 <sup>b</sup>	60.1	65.6	3.4
	DA	5.4 <sup>b</sup>	70.8	76.3	2.9
	RA-27	6.6 <sup>ab</sup>	74.9	81.6	3.3
	RA-37	9.7 <sup>a</sup>	69.3	79.0	3.3
	SE	1.1	2.4	2.7	0.3

<sup>¶</sup> a = the rapidly soluble material (%), b = the slowly degraded material (%), a+b = potentially degraded material (%), c = the rate of degradation (%/hr).  
a, b, c Least square means in the same column bearing different superscripts differ (P<0.05).



that once the ammoniated straw enter the rumen fluid it takes only a few minutes for the water-soluble-N to disappear from the sample. The remaining N is probably bound to cell wall. This will make the availability of soluble carbohydrate at feeding time as a crucial factor that determine the efficiency of N utilization in ammoniated straw based diet.

Table 8. Effect of ammoniation and reconstitution of barley straw on rumen degradation of crude protein (% DM basis)<sup>¶</sup>

Treatment	Time of incubation (hr)						
	0	2	4	6	12	24	48
NA	34.10	35.86	21.14	19.68	7.31	8.80	12.77
DA	45.59	46.63	40.94	37.13	31.06	33.73	40.74
RA-27	47.19	45.59	39.27	39.60	36.16	41.63	47.37
RA-37	49.73	49.97	41.53	41.30	41.02	45.62	47.32

<sup>¶</sup> corrected with microbial contamination.

## Experiment II

Influence of Protein and Energy Supplementation on Intake,  
Digestibility and Nitrogen Balance in Lambs Consuming  
Ammoniated Barley Straw

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Short title: Supplementation of ammoniated barley straw.

Key words : protein, energy, digestibility, lambs,  
ammoniated barley straw.

## ABSTRACT

A study was conducted to evaluate the effect of protein and energy supplementation of ammoniated barley straw in lambs. Forty growing lambs were factorially assigned to four dietary treatments in a randomized complete block design. Lambs were fed ammoniated straw at 65% and concentrate at 35% of dietary dry matter (DM) intake, during an intake, digestion and N balance trial. Concentrates were formulated to contain a combination of: rapidly released energy and low undegradable protein (BS); rapidly released energy and high undegradable protein (BF); slowly released energy and high undegradable protein (CF) and slowly released energy and low undegradable protein (CS). Fish meal and soybean meal were used as a source of protein, while barley grain and corn grain were used as an energy source in the concentrate.

No difference due to treatment was observed for feed intake ( $P > 0.05$ ). Digestibility of DM, organic matter (OM), neutral detergent fiber (NDF) and hemicellulose was influenced by energy source ( $P < 0.01$ ). The values for digestibility of BS, BF, CF and CS being: 64.8, 64.0, 67.5 and 68.4% for DM; 66.4, 66.5, 69.8 and 70.3% for OM; 59.8, 62.5, 69.2 and 66.9% for NDF; 78.1, 81.7, 88.3 and 84.8 for hemicellulose, respectively. Effect of protein source was significant for digestibility of hemicellulose only ( $P < 0.05$ ). Digestibility of DM and crude protein in straw,

calculated by difference, was higher for corn supplemented relative to barley supplemented diets ( $P < 0.01$ ). Plasma ammonia concentration for lambs consuming BF was higher than for lambs consuming other treatments ( $P < 0.01$ ). No differences were found in N balance, rumen pH, rumen VFA and rumen ammonia among treatments ( $P > 0.05$ ). It is suggested that a slow release energy supplement is required with ammoniated barley straw based diets to obtain a maximal digestibility in lambs.

## INTRODUCTION

Ammoniation is a well accepted method of improving the nutritive value of cereal straw. An elevated nitrogen (N) content and increased fiber digestibility are commonly obtained for low quality roughages materials after ammoniation (Williams 1984; Mason et al. 1988).

Increased moisture levels in straw before ammoniation enhanced the N retained after treatment (Mandell et al. 1988). However, from a previous study (manuscript 1) it is noted that the digestibility of crude protein of barley straw which had been reconstituted prior to ammoniation was reduced when fed to lambs with a barley grain supplementation.

Although ruminants are able to utilize non protein nitrogen as a source of protein, the amount of ammonia from ammoniated straw that can be utilized by the animals is determined by the rumen bacteria numbers, their rate of replication and availability of the ammonia nitrogen. Cellulolytic microbes need some amino acids for optimal feed fermentation (Huque and Thomsen 1984). Also conversion of ammonia to protein by microbia is dependent on how much energy is available from the fermentable feed consumed (Satter and Roffler 1977).

There has not been any data reporting a significant change in amino acids content of cereal straw after ammoniation. Males (1987) reported that only one half of

the added N in ammoniated straw was actually available to animals as a protein source. Although the digestibility of straw has been improved by ammoniation, its energy value remains low. This is due to the nature of straw which has a high content of structural carbohydrates but is low in readily available carbohydrates. Based on these facts, if ammoniated straw is to be used in the diet for purposes of obtaining rapid growth or increasing animal performance, a protein and energy supplement must be included. Use of ammoniated straw in this type of feeding system might enable rumen microbes to utilize the ammonia and digested fiber fraction to meet their nutrient requirements, while a major portion of protein and energy that escape rumen degradation would provide requirements of the host animal.

Fish meal and soybean meal are two kind of protein supplements commonly included in rations. The first supplement is known as having low protein degradability; while the second is highly degradable in the rumen. Barley and corn grains are two kinds of energy supplements which have different starch characteristics. Starch from barley grain is rapidly degraded in the rumen and, therefore, is capable of providing available energy immediately needed for ammonia incorporation by rumen microbia for protein synthesis. Starch from corn grain is more slowly degraded and, therefore, provides energy for rumen microbia for a longer period of time following ingestion.

This experiment was conducted to evaluate the effect

of protein degradability and the rate of release of energy supplements fed with ammoniated barley straw on voluntary intake, digestibility and N balance in growing lambs.



## MATERIAL AND METHODS

Twelve Outaouais and 28 crossbred Suffolk x Outaouais lambs were assigned into 4 treatment diets in a factorial arrangement of a randomized completely block design. Outaouais is a breed developed by Agriculture Canada, selected for meat production. The lambs averaging  $80.4 \pm 5.5$  days of age were blocked according to their initial body weights. Lambs had initial body weights of  $22.6 \pm 3.1$  kg and  $30.1 \pm 2.5$  kg for blocks 1 and 2, respectively. Two types of individual crates were used to house the lambs. Sixteen crossbred lambs were placed in raised slatted floor individual crates. The remainder of the lambs were placed into floor level individual crates. All animals were held for three weeks for a voluntary intake measurement. Only animals in raised slatted floor crates were held an additional 10 days for digestibility and N balance measurements.

All lambs recieved ammoniated barley straw and concentrate (table 9). Barley straw was ammoniated at 3.5 % (wt/wt, DM basis), after reconstitution to reach a moisture level of 27%. Ammoniation was carried out according to Sundstol et al. (1978). Anhydrous ammonia was injected into the straw stack from a pressurized tank through a metal hose. Weight of the tank was recorded to determined the time to stop ammonia injection after the appropriate amount of ammonia had been released. The stack was opened 28 days

Table 9. Ingredients and nutrient composition of concentrates and straw used in the lamb trial.

	Concentrate				Ammoniated straw
	BS	BF	CF	CS	
Ingredient, % DM basis					
Barley	83.4	86.3	-	-	
Corn	-	-	82.5	79.5	
Soybean meal (48%)	13.8	-	-	17.7	
Fish meal	-	11.0	14.7	-	
Premix <sup>¶</sup>	2.8	2.7	2.8	2.8	
Total	100.0	100.0	100.0	100.0	
Nutrient composition,					
CP, %DM	17.7	16.9	16.7	15.5	15.2
Undegradable CP, % CP <sup>§</sup>	30.3	39.5	60.0	46.6	ND
NDF, % DM	23.4	28.4	27.8	24.3	63.4
ADF, % DM	6.9	6.5	3.6	5.0	39.1
N E <sub>m</sub> , Mcal/kg <sup>Ⓒ</sup>	2.05	2.05	2.06	2.07	0.90

<sup>¶</sup> Composition per kg (DM basis): Ca:220 g, P:137 g, Na:1.40 g, I:122 mg, Fe:343 mg, Cu:5 mg, Mn:549 mg, Zn:245 mg. <sup>§</sup> Values are estimated from National Research Council (1989). <sup>Ⓒ</sup> Values are estimated from National Research Council (1985) ND: not determined.

after ammonia treatment. Subsequently, straw was aired and chopped with a forage harvester before being fed to the animals.

Straw was fed twice daily at 10:00 and 16:00 hr at 65 % of the dietary DM intake. The concentrates were given once daily together with the morning straw feeding at 35% of dietary DM intake. The experiment consisted of: 15 days of adaptation, 7 days of voluntary intake measurement, 3 days of adjustment to 90% of voluntary intake and 6 days of digestibility and N balance trial. Rumen liquor and blood samples were taken from the 24 lambs in floor crates one hour prior to and two hour following the morning feeding on two consecutive days following the 7 day intake measurement. Rumen samples were taken using an esophageal tube connected to a strained metal bolus (Ingalls et al. 1980). Rumen liquor pH and volatile fatty acid measurements were obtained as previously described (Manuscript 1). Blood samples, taken by venapuncture using heparinized vacutainers were centrifuged (2000 r.p.m., 10 minutes) and the plasma was stored ( $-20^{\circ}$  C) for ammonia analysis.

Urine samples were collected at 8:30 hr daily during the N balance trial. Twenty five ml of 10 N sulfuric acid was added in the urine receiver of each lamb. Fecal samples were collected twice daily at 9:30 and 16:30 hr. Feed samples, 20 % aliquot of fecal samples and 5% aliquot of urine samples were stored ( $-20^{\circ}$  C) immediately after collection.

Straw, concentrate and fecal samples were dried in a forced air oven (55° C) for 48 hours. Subsequently, samples were ground in a Wiley mill to pass a 1 mm screen. Dry matter (DM), crude protein (CP) and ash were determined according to Association of Official Analytical Chemist (1980). Neutral detergent fiber (NDF), and acid detergent fiber (ADF) were determined according to Goering and Van Soest (1970). Hemicellulose and organic matter (OM) content were calculated as the different between NDF and ADF and between DM and ash content, respectively. Rumen volatile fatty acid (VFA) analysis was determined by gas liquid chromatography according to Erwin et al. (1961). Blood plasma and rumen fluid ammonia were determined using Ion Selective Electrode (Orion Research Inc. Model 95-12). Apparent digestibility of ammoniated barley straw alone was calculated by difference, using values of 86, 87, 70 and 85% for barley grain, corn grain, fish meal and soybean meal for DM digestibility; while digestibility of CP was calculated as digestible protein divided by CP content for the respective feedstuffs (National Research Council 1985). Measurement of straw DM digestibility by difference by calculating total digestible nutrient value of supplement has been used by Streeter and Horn (1984).

Effects of protein and energy supplementation were compared using orthogonal linear contrast. All statistical analysis were permormed with General Linear Model (GLM) procedure according to Statistical Analysis System

(Statistical Analysis System Institute Inc. 1986).

## RESULTS AND DISCUSSION

Ammoniation of barley straw increased crude protein from 8.1 to 15.2% and decreased hemicellulose content from 30.2 to 24.3%, DM basis.

There was no difference in feed intake response due to source of protein or energy supplementation by lambs fed ammoniated barley straw ( $P>0.05$ , table 10). Compared with results from a previous trial (Manuscript 1), animals consumed (% BW) more straw in this experiment although the amount of concentrates offered was higher (35.0% vs 23.8% of DM intake).

Energy source influenced the digestibility of DM, OM, NDF and hemicellulose ( $P<0.01$ , table 10) but not of ADF and CP in the total diet ( $P>0.05$ ). Use of corn grain resulted in 9.7 and 14.5% higher DM ( $P<0.05$ ) and CP ( $P<0.01$ ) digestibilities for ammoniated straw, calculated by difference, compared with use of barley grain. Source of protein only affected the digestibility of hemicellulose in the diet. Digestibility of hemicellulose was greater when fish meal was supplemented in the ammoniated straw based diet rather than soybean meal ( $P<0.05$ ).

Since the higher digestibility of DM, OM, NDF and hemicellulose occurred in diets CF and CS which also contained higher undegradable protein levels, it is suggested that concentrates containing both slow release energy and high undegradable protein is needed to increase

Table 10. Effect of protein and energy supplementation of ammoniated straw on intake (n=10) and digestibility (n=4) in growing lambs (DM basis).

	Treatment				SE	Main effect comparisons <sup>¶</sup>	
	BS	BF	CF	CS		1	2
Intake,							
Total diet							
g d <sup>-1</sup>	1071.6	1015.1	998.9	1139.7	42.3	NS	NS
Straw							
g d <sup>-1</sup>	697.7	661.1	649.0	743.3	27.3	NS	NS
%BW	2.56	2.63	2.63	2.71	0.08	NS	NS
Digestibility,							
Total diet							
DM, %	64.8	64.0	67.5	68.4	0.9	**	NS
CP, %	64.0	62.3	61.3	62.0	1.0	NS	NS
OM, %	66.4	66.5	69.8	70.3	0.9	**	NS
NDF, %	59.8	62.5	69.2	66.9	1.5	**	NS
ADF, %	45.4	45.8	51.3	51.7	2.0	NS	NS
Hemicellulose,							
%	78.1	81.7	88.3	84.8	1.4	**	*
Straw							
DM, %	53.9	53.3	58.7	59.1	0.5	*	NS
CP, %	52.7	50.6	58.9	59.4	1.8	**	NS

<sup>¶</sup> Orthogonal contrast comparison of: 1 - energy source (BS+BF vs CF+CS) and 2 - protein source (BF+CF vs BS+CS).  
 NS: non significant (P>0.05); \*: significant (P<0.05);  
 \*\*: significant (P<0.01).

the utilization of ammoniated barley straw by lambs. Corn starch is more slowly degraded in the rumen than barley starch (Orskov et al. 1986). Without regard of processing technique, up to 27% of corn starch and 7% of barley starch may escape fermentation in the rumen (Theurer 1986). In diets with high proportion of fiber, a slower ruminal escape could result in a greater starch utilization by animals, which in turn provide a more synchronous availability of energy and nitrogen in the rumen. Greater digestibility of hemicellulose in diets with fish meal supplementation relative to those with soybean meal supplementation maybe because fish meal was more able to satisfy rumen microbial demand of amino acids. Growth of fiber digesting bacteria is stimulated by amino acids, peptides and branched chain volatile fatty acids (Huque and Thompsen 1984). Failure to show the effect of fish meal or soybean meal in other parameters observed in this trial suggests that a greater difference of the amount of undegradable protein in the diets being compared is required or that the limiting factor was energy. Assuming the contribution of undegradable protein by ammoniated straw is 0, diets with fish meal and soybean meal supplementation averaged 18.8 and 14.8% undegradable protein of total diet's protein, respectively.

No difference on N utilization as a result of protein and energy supplementation of ammoniated straw by lamb was observed ( $P > 0.05$ , table 11). This indicates that N absorbed



Table 11. Effect of protein and energy supplementation of ammoniated barley straw on N utilization by growing lambs (DM basis, n=4)<sup>¶</sup>.

Item	Treatment				SE
	BS	BF	CF	CS	
N intake,					
g d <sup>-1</sup>	24.0	19.8	23.3	22.9	1.3
Fecal N output,					
g d <sup>-1</sup>	8.6	7.5	9.0	8.7	0.6
Urinary N output,					
g d <sup>-1</sup> <sup>¶</sup>	11.9	9.7	12.9	10.7	1.3
N retention,					
g d <sup>-1</sup> <sup>¶</sup>	3.4	2.6	2.1	3.5	1.2
N balance,					
% <sup>¶</sup>	14.1	14.0	8.9	15.6	5.3

<sup>¶</sup> n=3 for urinary N output, N retention and N balance for treatment CF.

from all of the diets were utilized with the same efficiency by lambs.

Rumen pH was decreased, while total VFA concentration was increased after feeding (table 12). Differences in rumen pH and VFA concentration were not significant among treatments ( $P>0.05$ ). Plasma N concentration of treatment CF after feeding was higher than other treatments ( $P<0.01$ ). This implicates that conversion of ammonia to urea by liver was less efficient when more protein from fish meal was available in the rumen.

The reduced pH after feeding might have been due to increases in starch fermentation. Rumen ammonia concentrations after feeding were equally high in all treatments. This could happen because rumen liquor samples were taken when fermentation was achieving its peak (2 hr post feeding). The high rumen ammonia concentration was contributed by ammonia from ammoniated straw and degraded protein being released in the rumen. The concentration of rumen ammonia before feeding in the lambs seemed to be adequate for rumen microbial requirements as suggested by Satter and Roffler (1971). Some portion of ammonia could have been wasted by animals by adding high protein concentrate in this experiment. Adding an energy supplement would be more beneficial than protein supplementation of ammoniated straw based diets in lambs.

Table 12. Effect of protein and energy supplementation of ammoniated barley straw on rumen pH, total VFA and ammonia concentration and blood plasma ammonia concentration (n=5).

Item	Treatment				SE
	BS	BF	CF	CS	
Rumen pH					
before feeding	6.88	6.73	6.84	6.84	0.06
after feeding	6.42	6.50	6.59	6.51	0.04
Total VFA, mg dl <sup>-1</sup>					
before feeding	318.76	351.55	294.27	343.57	27.15
after feeding	474.08	495.78	437.81	484.32	35.51
Rumen ammonia, mg dl <sup>-1</sup>					
before feeding	4.67	5.29	6.02	5.45	0.95
after feeding	30.13	35.69	31.83	34.29	3.86
Plasma ammonia, mg dl <sup>-1</sup>					
before feeding	1.66	1.64	1.27	1.84	0.37
after feeding	1.28 <sup>b</sup>	3.62 <sup>a</sup>	1.54 <sup>b</sup>	1.75 <sup>b</sup>	0.15

a, b Means in the same row bearing different superscript differ (P<0.05).

## GENERAL DISCUSSION

### Chemical composition

Results of experiment I showed that dry ammoniation and a combination of reconstitution and ammoniation increased CP content of barley straw ( $P < 0.01$ ). Dry ammoniation increased CP content of straw by 30%, while in combination with reconstitution at 27 and 37% moisture the increases were 48 and 43 %, respectively. In experiment II the increase of CP after ammoniation was greater than in experiment I (87.5%) due to higher rate of ammonia applied. Although statistically not significant, reconstitution appears to increase CP retained in the straw after treatment.

Reconstitution increased the amount of N recovered in the fiber (ADIN). This increase seemed to be parallel with the temperature in the stacks. Increases in ADIN and ADF could have resulted from the non enzymatic browning (Maillard) reaction which formed indigestible carbon to N bonds between protein and sugars (Van Soest 1965). Dry ammoniation did not reduce the hemicellulose content of straw ( $P > 0.05$ ) while the hemicellulose content was reduced with reconstitution ( $P < 0.05$ ). The decrease in hemicellulose content in straw ammoniated at 27% moisture was 9 and 19% for experiment I and II, respectively. Addition of water and increased dosage of ammonia probably

enhanced the solubilization of hemicellulose in the straw (Streeter and Horn 1984). Ammonia has been reported as a fungicidal agent that can reduce mould growth in perennial grass treated in the stack (Woolford et al. 1984). In this experiment, the fungistatic properties of ammonia were reduced in the straw ammoniated at 37% moisture. It was shown by an elevated content of glucosamine, the hydrolysis end product of invading fungi.

### Intake and digestibility

In experiment I no difference in straw intake due to treatment was found ( $P > 0.05$ ). Type of protein and energy supplement did not affect ammoniated straw intake in experiment II ( $P > 0.05$ ). Lack of difference could be attributed to the fact that diets were formulated to be isonitrogenous and isocaloric in both experiments.

Only after reconstitution to 27% moisture did ammoniation influence DM and ADF digestibility in the diet ( $P < 0.05$ ). Reconstitution and ammoniation increased the digestibility of NDF and hemicellulose in comparison with diets containing dry ammoniated and non ammoniated straw ( $P < 0.05$ ). Data on the effects of reconstitution and ammoniation of straw is limited. Mandell et al. (1988) reported that reconstitution before ammoniation could improve the digestion of NDF, ADF, cellulose and

hemicellulose in wheat straw. Increased solubilization of hemicellulose has been proposed as a partial explanation (Streeter and Horn 1984). Ammoniation results in more fragile straw (Zorrilla-Rios et al. 1985). Adding water could have increased the particle disintegration and susceptibility of straw to microbial attack in the rumen, resulting in higher digestibility of cell wall.

In experiment II, the effect of source of energy in the supplement for reconstituted, ammoniated barley straw was significant for the digestibility of DM, OM, NDF and hemicellulose ( $P < 0.05$ ) but not of ADF and CP ( $P > 0.05$ ). Straw DM and CP digestibility calculated by difference were affected by the source of energy in the supplement ( $P < 0.05$ ). The effect of protein supplement was only significant for hemicellulose digestibility ( $P < 0.05$ ). Corn grain supplemented diets had greater digestibilities than those of barley grain supplemented diets. Corn grain has the characteristic of both slow releasing starch and protein in the rumen. This combination could have provided more synchronous energy and N over longer period required for maximizing digestion of feed by rumen microbes. Addition of fish meal appears to increase hemicellulose digestibility in comparison with soybean meal supplementation.

Data on CP digestibility in experiment I showed a conflicting result. CP digestibility of diet was reduced when ammoniated straw was fed to lambs in comparison with

nonammoniated straw. A reduction of CP digestibility due to ammoniation process has been reported (Smith et al. 1984 and Zorilla-Rios et al. 1989). However, a further reduction was observed if straw was reconstituted before ammoniation. Digestibility of straw alone, calculated by difference, showed that only straw ammoniated at 37% moisture had a reduced value ( $P < 0.05$ ). Animals consuming reconstituted straw excreted more N in the feces than those eating non ammoniated and dry ammoniated straw ( $P < 0.05$ ). Analysis on ADIN content of feces presented a significant difference among treatments ( $P < 0.05$ ) with order the reverse of the CP digestibility, ADIN values being 7.6, 9.1, 10.3 and 14.3 % of protein intake for animals consuming NA, DA, RA-27 and RA-37, respectively. However, when the ADIN content of straw and feces were accounted for, order of CP digestibility for straw treatment did not change. No difference in N balance was observed among treatments ( $P > 0.05$ ). It is suggested that the value of protein from ammonia or urea for animals in this trial is equal. The presence of ADIN in reconstituted and ammoniated straw contributes to the reduction of CP digestibility.

Results on CP digestibility in experiment II indicated that straw protein digestibility, calculated by difference, was higher if corn grain was used as the source of energy in the concentrate instead of barley grain. However source of protein or energy did not differently affect the digestibility of CP in the total diet ( $P > 0.05$ ).

The effects of treatments on rumen pH and VFA and blood urea N in Experiment I were not different ( $P>0.05$ ). It indicates that the ammonia being released in the rumen from urea or ammoniated straw did not influence fermentation and that increase of fiber digestibility was not great enough to influence concentration of VFA in the rumen fluid measured 2 hr after feeding. A similar trend happened in experiment II. Rumen pH, rumen ammonia and VFA concentration were not affected by treatment ( $P>0.05$ ) although their concentration changed with time of observation ( $P<0.01$ ). The diet containing a combination of barley grain and fish meal had a higher plasma ammonia nitrogen concentration after feeding than other treatments ( $P<0.05$ ) suggesting poor synchronization of energy and protein availability to rumen microbes and/or lambs. This experiment suggests that source of energy is more important in ammoniated straw based diets relative to source of protein.

#### Rumen degradation

Ammoniation did not significantly increase straw degradability in the rumen ( $P>0.05$ ). However, if accompanied with reconstitution to 37% moisture ammoniation increased the rapidly soluble DM and ADF fraction in the rumen. The potentially degradable DM fraction was affected



by reconstitution and ammoniation ( $P < 0.05$ ). Greater potentially degraded DM in straw reconstituted to 37% moisture relative to straw reconstituted to 27% is mainly due to the higher value of rapidly soluble DM, which does not necessarily reflect its digestibility. Rate of straw degradation was not affected by treatment ( $P > 0.05$ ). In general, data of nylon bag trial support the findings in lamb trial.

## SUMMARY AND CONCLUSION

1. Reconstitution of straw resulted in increased stack temperatures following ammoniation. This increase was accompanied by an increase in ADIN content. Reconstitution and ammoniation increased the crude protein and reduced the hemicellulose content of barley straw.
2. The digestibility of DM, NDF, ADF and hemicellulose of diet was increased if barley straw was ammoniated and reconstituted to 27% moisture prior to ammoniation.
3. Reduced protein digestibility occurred if reconstituted, ammoniated straw was incorporated in the diet of lambs.
4. Reconstitution to 37% moisture prior to ammoniation increased the degradation of rapidly soluble DM and ADF and increased the potential degradability of straw DM in the rumen.
5. Isocaloric supplementation of corn grain in place of barley grain as a source of energy in the concentrate for lambs fed reconstituted, ammoniated barley straw increased the digestibility of DM, OM, NDF and hemicellulose of diet.

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**APPENDICES**

Appendix 1. Temperature ( $^{\circ}\text{C}$ ) of straw stacks at the first 10 days after ammoniation( $n=2$ ). Experiment 1.

Day	Treatment			
	NA	DA	RA-27	RA-37
1	23.2	29.5	30.4	31.7
2	16.2	23.9	37.2	41.8
3	14.7	20.9	27.4	33.5
4	18.1	18.2	22.3	27.6
5	24.8	23.6	27.6	29.2
6	19.8	22.6	27.2	30.0
7	21.6	21.4	23.8	28.3
8	25.7	22.4	22.8	28.9
9	22.8	24.0	27.1	30.8
10	26.1	25.9	26.1	32.0

Appendix 2. Chemical composition of grain mix fed to the lambs (DM basis). Experiment 1<sup>¶</sup>

Item	Treatment			
	NA	DA	RA-27	RA-37
CP, %	23.5	14.5	13.8	13.6
NDF, %	21.5	23.1	25.1	24.6
ADF, %	6.3	6.1	6.6	6.2
Hemicellulose, %	15.2	17.0	18.5	18.5
Ash, %	8.5	8.0	7.9	8.5

<sup>¶</sup> A mineral premix (Composition: Ca: 2.5 g, P:1.4 g, S:60 mg, I:1.2 mg, Fe:3.5 mg, Cu:0.05 mg, Co:0.05 mg, Mn: 28.6 mg, Zn:5.0 mg kg<sup>-1</sup> diet) was added to the grain at the rate of 54 g kg<sup>-1</sup>, DM basis. A 0.5 ml sodium selenite preparation was injected intramuscularly at the beginning of experiment.



Appendix 3. Analysis of variance for chemical composition  
of barley straw. Experiment 1.

PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR > F
CP	TRT	3	15.41547500	11.60	0.0007
	ERROR	12	5.31750000		
NDF	TRT	3	29.09161875	2.18	0.1427
	ERROR	12	53.26387500		
ADF	TRT	3	14.19135000	4.21	0.0299
	ERROR	12	13.48955000		
ADIN	TRT	3	0.02398105	11.71	0.0007
	ERROR	12	0.00819333		
HEMICEL- LULOSE	TRT	3	83.35061875	20.07	0.0001
	ERROR	12	16.61312500		
ASH	TRT	3	6.47767500	2.61	0.0995
	ERROR	12	9.92050000		
GLUCO- SAMINE	TRT	3	35.53285460	5.10	0.0115
	ERROR	16	37.14283760		

TRT= treatment

Appendix 4. Individual data on the feed intake of lambs  
(DM basis). Experiment 1.

Period	Animal No.	Treatment	DM intake		Grain g d <sup>-1</sup>	Total g d <sup>-1</sup>
			g d <sup>-1</sup>	Straw % BW		
I	1	NA	334.4	1.3	94.3	428.7
	2	DA	331.9	1.3	100.4	432.3
	3	RA-27	538.1	1.9	152.5	690.6
	4	RA-37	582.0	2.1	155.5	737.5
II	3	NA	630.9	2.2	221.0	851.9
	4	DA	601.6	2.2	203.3	804.9
	2	RA-27	662.6	2.4	194.3	856.9
	1	RA-37	660.3	2.4	197.1	857.3
III	2	NA	550.9	2.0	162.4	713.3
	1	DA	722.4	2.4	205.7	928.1
	4	RA-27	683.3	2.3	246.7	930.0
	3	RA-37	709.9	2.3	269.6	979.4
IV	4	NA	741.0	2.3	225.7	966.8
	3	DA	749.5	2.3	247.4	996.9
	1	RA-27	780.4	2.5	235.7	1016.1
	2	RA-37	595.0	2.2	182.0	777.0

Appendix 5. Individual data on the DM digestibility of total diet and straw in lambs (DM basis) Experiment 1.

Period	Animal No.	Treatment	Digestibility (%)	
			Total diet	Straw
I	1	NA	57.0	50.4
	2	DA	54.7	47.4
	3	RA-27	58.3	52.1
	4	RA-37	53.4	45.7
II	3	NA	54.6	49.0
	4	DA	55.0	53.7
	2	RA-27	59.5	47.3
	1	RA-37	55.9	47.8
III	2	NA	54.7	50.5
	1	DA	57.0	47.4
	4	RA-27	59.9	52.9
	3	RA-37	58.9	54.2
IV	4	NA	57.1	56.6
	3	DA	56.0	49.8
	1	RA-27	61.7	50.6
	2	RA-37	56.5	47.3

Appendix 6. Analysis of variance for dry matter intake and digestibility. Experiment 1.

PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR > F
<b>Intake,</b>					
Total diet g d <sup>-1</sup>	PER	3	321248.56431875	16.30	0.0027
	AN	3	82399.70136875	4.18	0.0644
	TRT	3	40184.84256875	2.04	0.2099
	ERROR	6	39408.71793751		
Straw g d <sup>-1</sup>	PER	3	167475.23381875	10.33	0.0088
	AN	3	38370.36291875	2.37	0.1700
	TRT	3	23303.31696875	1.44	0.3220
	ERROR	6	32433.61978750		
%BW	PER	3	1.16555000	7.72	0.0175
	AN	3	0.13745000	0.91	0.4900
	TRT	3	0.34755000	2.30	0.1772
	ERROR	6	0.30215000		
<b>Digestibility,</b>					
Total diet DM	PER	3	11.85515000	1.97	0.2200
	AN	3	6.51675000	1.08	0.4251
	TRT	3	46.89375000	7.79	0.0172
	ERROR	6	12.03915000		

BW= Body weight, PER= period. AN= animal, TRT= treatment.

Appendix 7. Individual data on fiber digestibility of total diet in lambs (DM basis). Experiment 1.

Period	Animal No.	Treatment	Digestibility		
			NDF %	ADF %	Hemicellulose %
I	1	NA	58.4	53.2	68.0
	2	DA	56.6	51.6	66.2
	3	RA-27	63.7	56.2	78.0
	4	RA-37	57.2	50.1	74.3
II	3	NA	53.5	47.9	63.7
	4	DA	56.8	50.7	68.2
	2	RA-27	65.4	58.1	79.0
	1	RA-37	60.7	51.3	82.2
III	2	NA	52.8	47.7	62.3
	1	DA	57.4	51.2	69.0
	4	RA-27	63.1	56.4	75.9
	3	RA-37	62.1	55.5	76.4
IV	4	NA	57.7	51.9	67.9
	3	DA	57.0	51.3	67.2
	1	RA-27	66.5	59.3	81.0
	2	RA-37	59.8	53.0	74.9

Appendix 8. Analysis of variance for fiber digestibility  
of total diet. Experiment 1.

PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR >F
NDF	PER	3	4.78946875	0.34	0.7949
	AN	3	11.77566875	0.85	0.5169
	TRT	3	192.80696875	13.86	0.0042
	ERROR	6	27.8208750		
ADF	PER	3	7.03895000	0.40	0.7556
	AN	3	4.95485000	0.28	0.8351
	TRT	3	127.05575000	7.30	0.0199
	ERROR	6	34.85275000		
HEMI- CELLULOSE	PER	3	13.81051875	1.27	0.3672
	AN	3	47.84291875	4.39	0.0587
	TRT	3	513.43286875	47.07	0.0001
	ERROR	6	21.81438750		

Appendix 9. Analysis of variance for DM and CP digestibility of barley straw, calculated by difference. Experiment 1.

PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR >F
DM	PER	3	20.41724361	1.97	0.2200
	AN	3	11.22331411	1.08	0.4251
	TRT	3	80.76161986	7.79	0.0172
	ERROR	6	20.73413313		
CP	PER	3	876.39295842	41.16	0.0002
	AN	3	40.18107112	1.89	0.2327
	TRT	3	1520.64447010	71.42	0.0001
	ERROR	6	42.58152672		

Appendix 10. Individual data on N utilization and protein digestibility in lambs (DM basis). Experiment 1.

PER <sup>1</sup>	AN	TRT	NI	NF	NU	NR	NBAL	DCP
I	1	NA	6.3	2.2	3.2	0.9	14.6	65.5
	2	DA	5.9	2.6	2.5	0.7	12.6	55.4
	3	RA-27	10.1	4.7	3.1	2.2	22.3	53.3
	4	RA-37	10.7	5.6	2.1	3.0	27.9	47.4
II	3	NA	12.9	4.7	4.9	3.2	25.2	63.2
	4	DA	10.4	4.9	2.9	2.6	25.4	53.0
	2	RA-27	11.2	6.1	3.3	1.8	15.9	45.5
	1	RA-37	10.6	6.0	1.9	2.7	25.2	43.0
III	2	NA	8.7	4.1	2.2	2.4	27.2	52.8
	1	DA	10.0	5.3	2.7	1.9	19.3	46.9
	4	RA-27	11.7	7.0	2.5	2.2	18.7	40.2
	3	RA-37	10.6	6.8	1.3	2.5	23.9	35.8
IV	4	NA	12.8	5.6	4.6	2.6	20.1	56.0
	3	DA	11.7	7.1	2.5	2.1	17.7	39.5
	1	RA-27	12.4	7.5	2.3	2.5	20.3	39.3
	2	RA-37	9.2	6.4	1.6	1.1	12.3	30.2

<sup>1</sup> PER: period; AN : animal number; TRT: treatment; NI: N intake,  $g d^{-1}$ ; NF: fecal N output,  $g d^{-1}$ ; NU: urinary N output,  $g d^{-1}$ ; NR: N retention,  $g d^{-1}$ ; NBAL: N balance, %; DCP: digestibility of crude protein, %.



Appendix 11. Analysis of variance for nitrogen utilization and protein digestibility in total diet. Experiment 1.

PARAMETER <sup>¶</sup>	SOURCE	DF	TYPE III SS	F VALUE	PR> F
NI	PER	3	26.37726464	6.22	0.0285
	AN	3	19.37332736	4.57	0.0542
	TRT	3	7.16931200	1.69	0.2671
	ERROR	6	8.47775872		
NU	PER	3	2.23371650	1.79	0.2487
	AN	3	1.01970450	0.82	0.5295
	TRT	3	8.18743850	6.57	0.0253
	ERROR	6	2.49353250		
NF	PER	3	17.40804577	22.32	0.0012
	AN	3	2.75228631	3.53	0.0883
	TRT	3	13.08611634	16.78	0.0025
	ERROR	6	1.56005812		
NR	PER	3	1.52385965	1.25	0.3709
	AN	3	3.09805374	2.55	0.1519
	TRT	3	0.57648468	0.47	0.7115
	ERROR	6	2.43117593		
NBAL	PER	3	74.39765749	0.83	0.5235
	AN	3	88.84137021	0.99	0.4575
	TRT	3	38.17631796	0.43	0.7413
	ERROR	6	179.00455888		
DCP	PER	3	508.87231295	41.16	0.0002
	AN	3	23.33089786	1.89	0.2327
	TRT	3	882.95308770	71.42	0.0001
	ERROR	6	24.72470800		

<sup>¶</sup> NI: N intake ; NU: Urinary N output; NF: Fecal N output; NR: N retention; N-BAL: N balance; DCP: Digestibility of crude protein.

Appendix 12. Analysis of variance for rumen VFA, pH and blood ammonia. Experiment 1.

PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR >F
ACETATE	PER	3	9956.09056667	5.24	0.0529
	AN	3	3779.50406667	1.99	0.2340
	TRT	3	1720.33428889	0.91	0.5005
	ERROR	5	3164.75813333		
PROPIO- NATE	PER	3	873.03200500	12.11	0.0099
	AN	3	979.87787222	13.59	0.0077
	TRT	3	86.35637222	1.20	0.4000
	ERROR	5	120.15348333		
ISOBUTY- RATE	PER	3	0.96807220	1.75	0.2721
	AN	3	0.39538889	0.72	0.5836
	TRT	3	2.65005556	4.80	0.0621
	ERROR	5	0.92078333		
BUTYRATE	PER	3	845.52416667	0.99	0.4690
	AN	3	442.88022222	0.52	0.6881
	TRT	3	407.73480556	0.48	0.7122
	ERROR	5	1425.55088333		
ISOVALE- RATE	PER	3	16.99275556	1.33	0.3620
	AN	3	10.57635556	0.83	0.5315
	TRT	3	44.79778889	3.52	0.1046
	ERROR	5	21.21960000		
VALERATE	PER	3	2.09353889	1.74	0.2744
	AN	3	3.36651667	2.80	0.1484
	TRT	3	2.62411667	2.18	0.2087
	ERROR	5	2.00628333		
TVFA	PER	3	3994.07858889	4.62	0.0664
	AN	3	10579.02740556	2.04	0.2275
	TRT	3	4050.05895556	0.78	0.5539
	ERROR	5	8657.08248333		
RUMEN PH	PER	3	0.02331667	0.33	0.8075
	AN	3	0.10656667	1.49	0.3245
	TRT	3	0.02340556	0.33	0.8066
	ERROR	5	0.11923333		
BLOOD UREA-N	PER	3	9.06687500	1.52	0.3030
	AN	3	4.83187500	0.81	0.5334
	TRT	3	18.54687500	3.11	0.1103
	ERROR	6	11.94375000		

Appendix 13. Composition of diet fed to steers in nylon bag trial (DM basis). Experiment 1.

Item	%	Nutrient Composition (%)				
		CP	NDF	ADF	Ca	P
Straw	20	5.1	81.3	54.2	0.4	0.1
Grain	10	12.2	25.9	6.7	1.8	1.6
Grass-hay	70	15.9	49.8	36.2	1.0	0.2

Appendix 14. Analysis of variance for rumen DM degradation  
of barley straw. Experiment 1.

PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR> F
a	TRT	3	143.50221457	18.74	0.0019
	AN	2	0.83178519	0.16	0.8533
	TRT*AN	6	15.31294423	0.67	0.6799
	ERROR	8	30.59212586		
b	TRT	3	396.77573477	2.58	0.1493
	AN	2	390.59874890	3.81	0.0856
	TRT*AN	6	307.87007461	0.54	0.7625
	ERROR	8	753.58481226		
c	TRT	3	0.00002821	0.23	0.8696
	AN	2	0.00051268	6.38	0.0327
	TRT*AN	6	0.00024106	0.59	0.7336
	ERROR	8	0.00054733		
a+b	TRT	3	868.33236029	5.24	0.0410
	AN	2	405.44759806	3.67	0.0910
	TRT*AN	6	331.47501903	0.55	0.7609
	ERROR	8	807.93030071		

Appendix 15. Analysis of variance for rumen NDF  
degradation of barley straw. Experiment 1.

PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR >F
a	TRT	3	45.68905646	3.29	0.1001
	AN	2	9.28797018	1.00	0.4212
	TRT*AN	6	27.80259234	1.14	0.4296
	ERROR	7	28.53483223		
b	TRT	3	483.32346424	4.22	0.0634
	AN	2	155.76703603	2.04	0.2111
	TRT*AN	6	229.21565959	3.49	0.0634
	ERROR	7	76.67362386		
c	TRT	3	0.00005875	0.51	0.6914
	AN	2	0.00041676	5.40	0.0456
	TRT*AN	6	0.00023154	1.12	0.4352
	ERROR	7	0.00024046		
a+b	TRT	3	334.02059324	1.87	0.2348
	AN	2	199.66187101	1.68	0.2633
	TRT*AN	6	356.43829504	2.88	0.0965
	ERROR	7	144.55507825		

Appendix 16. Analysis of variance for rumen ADF  
degradation of barley straw. Experiment 1.

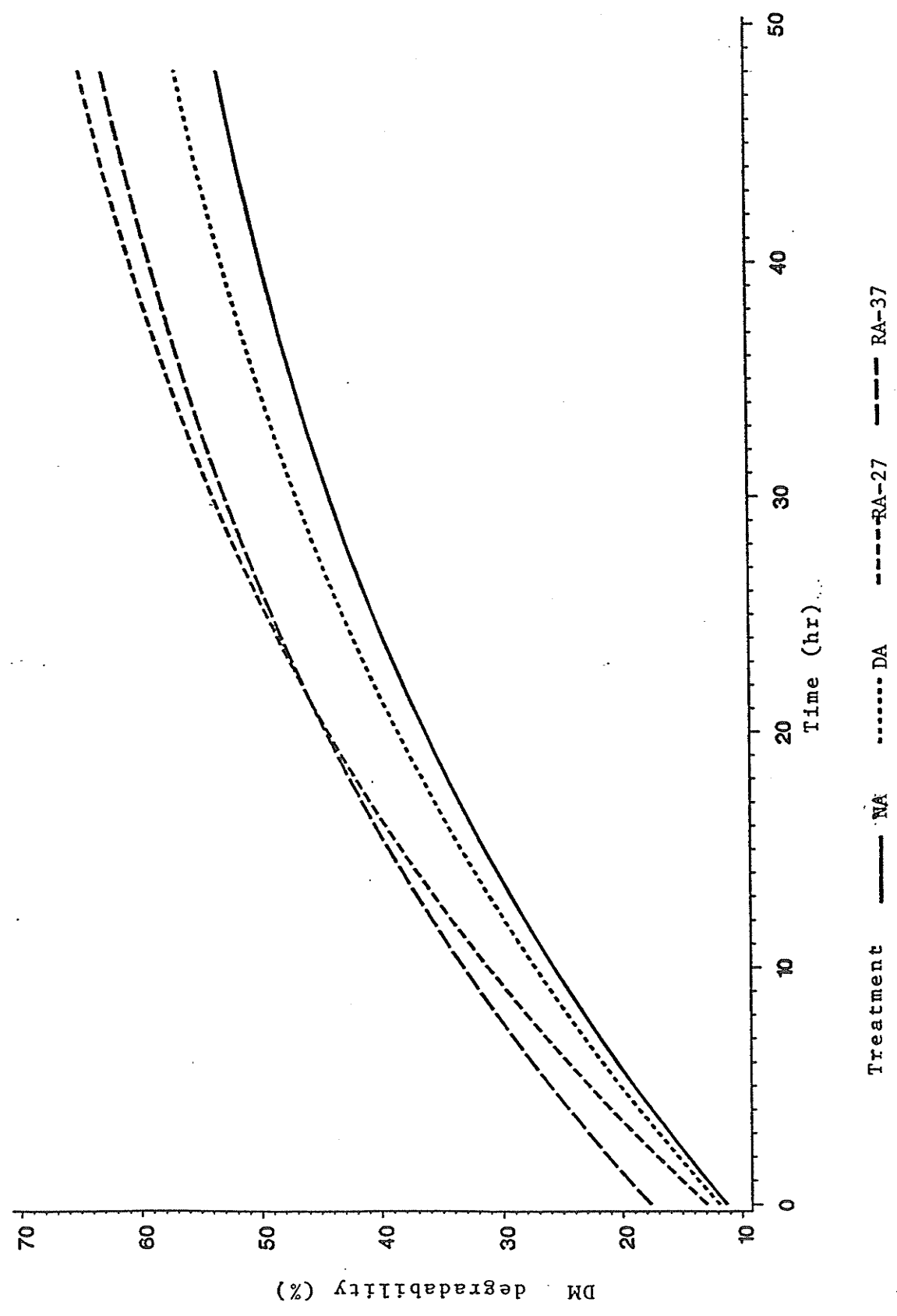
PARAMETER	SOURCE	DF	TYPE III SS	F VALUE	PR > F
a	TRT	3	64.89194337	4.63	0.0527
	AN	2	0.05952352	0.01	0.9937
	TRT*AN	6	28.01477946	0.82	0.5867
	ERROR	8	45.79583192		
b	TRT	3	562.54477314	2.34	0.1724
	AN	2	78.15820751	0.49	0.6360
	TRT*AN	6	479.99246342	2.95	0.0799
	ERROR	8	217.01759323		
c	TRT	3	0.00008393	0.38	0.7682
	AN	2	0.00033641	2.31	0.1800
	TRT*AN	6	0.00043626	1.76	0.2243
	ERROR	8	0.00033006		
a+b	TRT	3	731.81625665	2.79	0.1316
	AN	2	82.52923472	0.47	0.6450
	TRT*AN	6	524.28886056	2.50	0.1149
	ERROR	8	279.39827102		

Appendix 17 figure 2. Effect of ammoniation and reconstitution of barley straw on rumen DM degradation (%) at different time of incubation (hr).

Regression equation:

$$\begin{aligned} \text{NA} &= 11.3 + 54.5 ( 1 - 2.71828^{-3.1t} ) \\ \text{DA} &= 11.9 + 60.8 ( 1 - 2.71828^{-2.9t} ) \\ \text{RA-27} &= 12.9 + 66.2 ( 1 - 2.71828^{-3.3t} ) \\ \text{RA-37} &= 17.7 + 64.3 ( 1 - 2.71828^{-3.0t} ) \end{aligned}$$

t= time (hr)



Treatment — NA ..... DA - - - - - RA-27 - . - . - RA-37

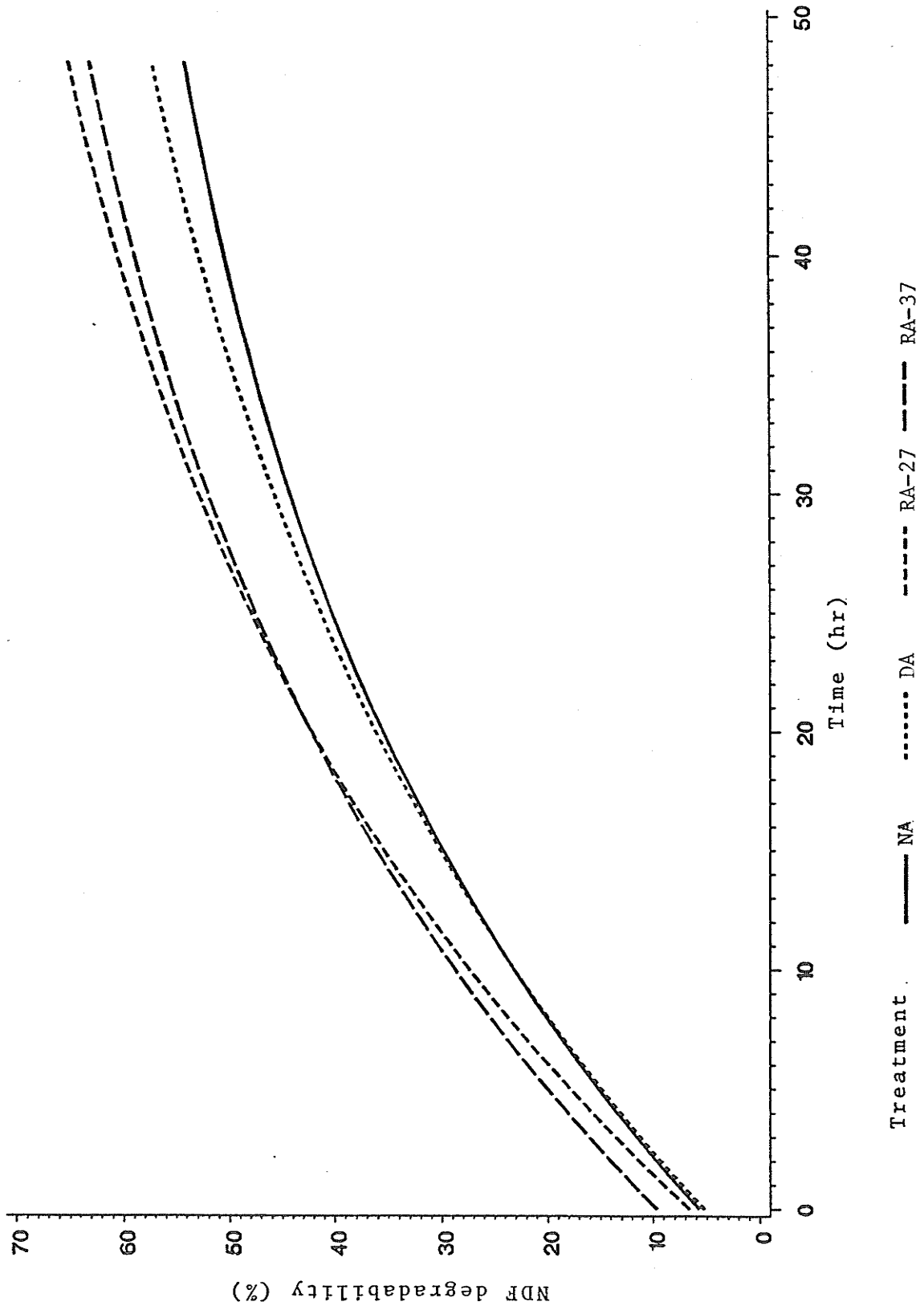


Appedix 18 figure 3. Effect of ammoniation and reconstitution of barley straw on rumen NDF degradation (%) at different time of incubation (hr).

Regression equation:

$$\begin{aligned} \text{NA} &= 7.3 + 63.1 ( 1 - 2.71828^{-3.0t} ) \\ \text{DA} &= 8.4 + 68.9 ( 1 - 2.71828^{-2.7t} ) \\ \text{RA-27} &= 5.3 + 77.8 ( 1 - 2.71828^{-3.2t} ) \\ \text{RA-37} &= 4.9 + 71.0 ( 1 - 2.71828^{-3.2t} ) \end{aligned}$$

t= time (hr)

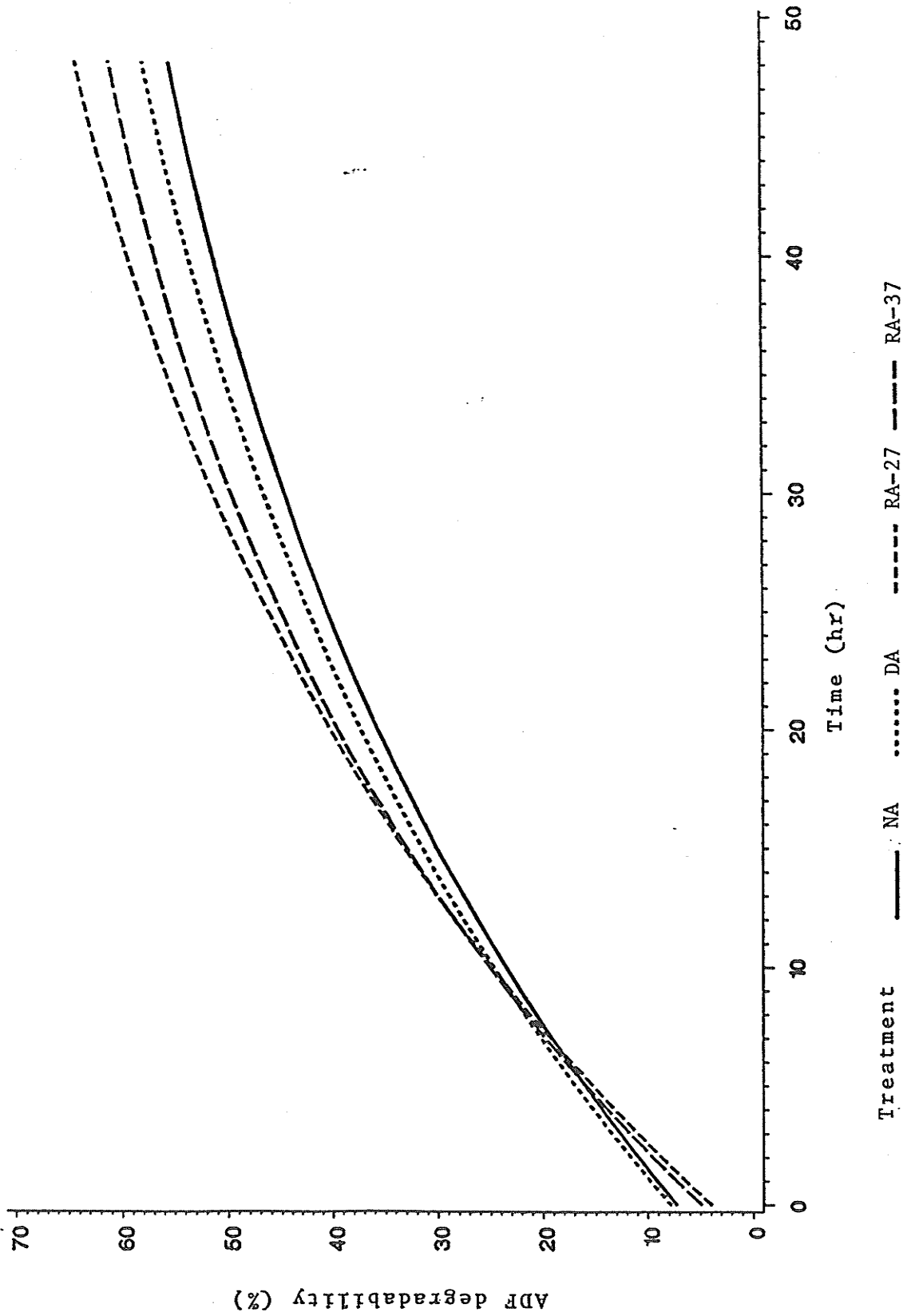


Appedix 19 figure 4. Effect of ammoniation and reconstitution of barley straw on rumen ADF degradation (%) at different time of incubation (hr).

Regression equation:

$$\begin{aligned} \text{NA} &= 5.7 + 60.1 ( 1 - 2.71828^{-3.4t} ) \\ \text{DA} &= 5.4 + 70.8 ( 1 - 2.71828^{-2.9t} ) \\ \text{RA-27} &= 6.6 + 74.9 ( 1 - 2.71828^{-3.3t} ) \\ \text{RA-37} &= 9.7 + 69.3 ( 1 - 2.71828^{-3.3t} ) \end{aligned}$$

t= time (hr)



Appendix 20. Individual data on dry matter intake in lambs (DM basis). Experiment 2.

Trt	An	Br	Bl	Cr	Total diet g d <sup>-1</sup>	Straw g d <sup>-1</sup>	Concentrate g d <sup>-1</sup>	Straw %BW
BS	6	2	1	1	981.6	639.5	342.1	2.6
	10	2	1	1	1045.5	680.4	365.1	2.7
	12	1	1	1	928.9	605.0	323.9	2.4
	18	2	2	1	1172.2	763.2	408.9	2.1
	19	1	2	1	1020.4	665.2	355.2	2.3
	22	1	2	1	1210.7	787.7	422.9	2.3
	25	1	1	2	872.6	568.3	304.2	3.2
	28	1	2	2	1265.6	823.2	442.4	2.7
	36	1	2	2	1226.1	797.7	428.4	2.6
	37	1	1	2	992.1	646.5	345.6	2.7
BF	1	1	1	1	941.9	613.2	328.8	3.1
	9	2	1	1	1042.7	688.9	353.8	2.6
	11	1	1	1	1107.9	719.8	388.1	2.7
	15	2	2	1	978.6	636.7	341.9	2.3
	17	1	2	1	1223.8	794.9	428.9	2.7
	20	2	2	1	1182.8	767.8	415.1	2.7
	26	1	2	2	1235.5	802.5	433.0	2.8
	31	1	1	2	664.2	433.6	230.6	2.8
	34	1	2	2	881.5	573.4	308.0	1.9
	35	1	1	2	891.5	579.9	311.6	2.6
CF	2	1	1	1	893.4	580.9	312.4	2.7
	3	2	1	1	777.0	506.9	270.1	2.4
	5	1	1	1	788.1	512.8	275.3	2.9
	8	2	1	1	799.3	520.1	279.2	2.3
	13	2	2	1	1102.1	715.6	386.5	2.5
	24	1	2	1	1267.1	822.3	444.8	2.7
	27	1	1	2	1038.5	673.9	364.6	2.9
	33	1	1	2	891.3	580.3	311.0	2.7
	38	1	2	2	1256.1	814.7	441.4	2.7
	40	1	2	2	1175.7	762.6	413.1	2.5
CS	4	2	1	1	1002.3	653.9	348.4	2.5
	7	1	1	1	1002.8	653.7	349.1	2.9
	14	2	2	1	1240.9	807.6	433.4	2.8
	16	1	2	1	1174.9	773.6	401.3	2.7
	21	2	2	1	1078.0	702.2	374.8	2.2
	23	1	2	1	1466.0	954.2	511.8	2.7
	29	1	1	2	989.9	645.8	344.1	3.0
	30	1	2	2	1090.5	710.3	380.2	2.8
	32	1	2	2	1154.9	751.8	403.1	2.5
	39	1	1	2	1197.1	779.7	417.4	3.0

Trt=treatment, An=animal, Br=breed, Bl=block. Cr=crate.

Appendix 21. Analysis of variance for dry matter intake in lambs. Experiment 2.

Parameter	Source	Df	Type III SS	F Value	Pr > F
Total diet g d <sup>-1</sup>	TR	3	46205.25278858	0.86	0.4763
	BR	1	12268.97653548	0.69	0.4167
	BL	1	237670.01390250	13.27	0.0014
	CR	1	11096.26724002	0.62	0.4395
	TR*BR	3	40689.53238252	0.76	0.5299
	TR*BL	3	44005.02754619	0.82	0.4971
	CR*BL	1	3448.74853500	0.19	0.6650
	TR*BR*BL	4	22818.50560386	0.32	0.8624
	ERROR	22	393890.46810197		
Straw g d <sup>-1</sup>	TR	3	20483.15725028	0.92	0.4484
	BR	1	4852.99376535	0.65	0.4278
	BL	1	96773.75014323	13.01	0.0016
	CR	1	4925.54149402	0.66	0.4245
	TR*BR	3	18065.12845316	0.81	0.5020
	TR*BL	3	19190.37298320	0.86	0.4764
	CR*BL	1	1625.83381500	0.22	0.6447
	TR*BR*BL	4	11020.30099670	0.37	0.8271
	ERROR	22	163609.60937249		
Straw %BW	TR	3	0.10557340	0.54	0.6589
	BR	1	0.25741232	3.96	0.0591
	BL	1	0.24212131	3.73	0.0666
	CR	1	0.00519187	0.08	0.7801
	TR*BR	3	0.03715850	0.19	0.9017
	TR*BL	3	0.14302738	0.73	0.5430
	CR*BL	1	0.00601183	0.09	0.7639
	TR*BR*BL	4	0.11434660	0.44	0.7784
	ERROR	22	1.42961599		

Appendix 22. Individual data on diet digestibility in lamb  
(DM basis). Experiment 2.

Animal no.	Trt	Block	Digestibility (%)					
			DM	CP	OM	NDF	ADF	Hemi
25	BS	1	63.4	64.7	65.0	56.1	41.9	74.1
28		2	67.2	66.8	68.4	62.0	48.9	78.6
36		2	63.0	61.7	64.6	58.7	42.3	79.5
37		1	65.7	62.7	67.6	62.4	48.5	80.1
31	BF	1	64.6	62.8	67.0	62.1	46.1	80.7
26		2	63.6	60.8	65.8	62.6	47.1	80.4
34		2	61.7	61.4	64.3	58.9	40.1	80.7
35		1	66.1	64.1	68.8	66.4	50.1	85.1
27	CF	1	65.8	57.5	68.4	68.8	52.0	86.7
33		1	68.5	61.8	70.8	71.9	51.9	93.1
38		2	66.5	61.9	68.9	66.3	47.7	86.0
40		2	69.0	64.0	71.3	69.8	53.5	87.3
29	CS	1	66.8	60.4	68.6	63.3	46.4	83.1
30		2	68.6	62.3	70.7	66.8	52.6	83.6
32		2	68.1	61.0	70.0	67.8	53.6	84.7
39		1	70.0	64.3	71.8	69.6	54.2	87.8

Hemi=hemicellulose.

Appendix 23. Analysis of variance for diet digestibility.  
Experiment 2.

Parameter	Source	Df	Type III SS	F Value	Pr >F
DM	TR	3	52.66118737	5.25	0.0271
	BL	1	0.70190884	0.21	0.6591
	TR*BL	3	7.44214899	0.74	0.5566
	ERROR	8	26.76140630		
CP	TR	3	15.14347048	1.13	0.3916
	BL	1	0.12536911	0.03	0.8708
	TR*BL	3	17.10127016	1.28	0.3449
	ERROR	8	35.58243407		
NDF	TR	3	215.59978985	7.84	0.0091
	BL	1	3.68820374	0.40	0.5437
	TR*BL	3	15.37734592	0.56	0.6568
	ERROR	8	73.36346223		
ADF	TR	3	139.30159894	2.98	0.0964
	BL	1	1.82986537	0.12	0.7406
	TR*BL	3	28.57277941	0.61	0.6264
	ERROR	8	124.64132635		
HEMI	TR	3	225.94407473	9.88	0.0046
	BL	1	6.41629019	0.84	0.3857
	TR*BL	3	15.37617871	0.67	0.5926
	ERROR	8	60.97712292		



Appendix 24. Analysis of variance for DM and CP  
 digestibility of ammoniated barley straw in lambs.  
 Experiment 2.

Parameter	Source	Df	Type III SS	F Value	Pr >F
DM	TR	3	112.99350802	4.43	0.0410
	BL	1	1.8519625	0.22	0.6532
	TR*BL	3	21.52077439	0.84	0.5075
	ERROR	8	68.03501509		
CP	TR	3	233.58887797	6.39	0.0162
	BL	1	0.2640090	0.02	0.8867
	TR*BL	3	50.17859679	1.37	0.3194
	ERROR	8	97.55068579		

Appendix 25. Individual data on nitrogen balance trial  
(g d<sup>-1</sup>) in lambs. Experiment 2.

AN	TR	BL	NI	NF	NU	NR	NBAL
25	BS	1	18.7	6.6	9.1	3.0	15.9
28		2	27.9	9.3	10.7	8.0	28.6
36		2	27.4	10.5	15.8	1.1	4.1
37		1	21.9	8.2	12.0	1.7	7.8
31	BF	1	14.7	5.4	4.6	4.6	31.6
26		2	26.0	10.2	11.9	3.9	15.1
34		2	19.3	7.4	12.6	-0.7	- 3.8
35		1	19.2	6.9	9.8	2.5	13.3
27	CF	1	21.9	9.3	9.5	3.1	14.1
33		1	19.5	7.5	MD	MD	MD
38		2	26.7	10.1	15.5	1.0	3.9
40		2	25.1	9.0	13.9	2.2	8.8
29	CS	1	19.9	7.9	7.4	4.6	23.3
30		2	22.6	8.5	10.8	3.3	14.6
32		2	24.1	9.4	12.9	1.8	7.5
39		1	25.1	9.0	11.8	4.3	17.1

MD= missing data.

Appendix 26. Analysis of variance for nitrogen balance in  
lambs. Experiment 2.

Parameter	Source	Df	Type III SS	F Value	Pr > F
TNI	TR	3	41.41740180	1.95	0.1995
	BL	1	90.88428556	12.86	0.0071
	TR*BL	3	23.08065362	1.09	0.4077
	ERROR	8	56.51778376		
NF	TR	3	5.14585106	1.37	0.3207
	BL	1	11.91216196	9.49	0.0151
	TR*BL	3	3.11507203	0.83	0.5149
	ERROR	8	10.03872195		
NU	TR	3	13.41448742	0.71	0.5785
	BL	1	50.50627512	7.97	0.0257
	TR*BL	3	6.51293446	0.34	0.7958
	ERROR	7	44.37683883		
NR	TR	3	3.57721883	0.21	0.8845
	BL	1	2.24275021	0.40	0.5472
	TR*BL	3	11.96422716	0.71	0.5754
	ERROR	7	44.37683883		
NBAL	TR	3	47.55024595	0.15	0.9259
	BL	1	190.12983263	1.81	0.2205
	TR*BL	3	231.63112749	0.73	0.5636
	ERROR	7	735.46883549		

Appendix 27. Effect of protein and energy supplementation of ammoniated barley straw on VFA concentration (n=5). Experiment 2.

Item	Treatment				SE
	BS	BF	CF	CS	
Acetate, mg dl <sup>-1</sup>					
before feeding	187.04	203.70	171.37	195.42	15.57
after feeding	294.63	308.08	277.35	300.87	22.42
Propionate, mg dl <sup>-1</sup>					
before feeding	65.45	69.60	60.71	72.41	5.82
after feeding	103.35	104.02	92.05	107.78	9.95
Isobutyrate, mg dl <sup>-1</sup>					
before feeding	4.46	4.89	4.67	5.37	0.45
after feeding	3.34	4.09	2.69	3.30	0.39
Butyrate, mg dl <sup>-1</sup>					
before feeding	50.03	59.95	45.20	55.42	7.44
after feeding	59.94	64.30	54.17	59.12	6.35
Isovalerate, mg dl <sup>-1</sup>					
before feeding	7.37	8.64	8.40	10.42	0.76
after feeding	4.98	6.49	4.4	6.45	0.73
Valerate, mg dl <sup>-1</sup>					
before feeding	4.39	4.77	4.12	4.53	0.45
after feeding	7.84	8.80	7.15	6.80	0.60
Total VFA, mg dl <sup>-1</sup>					
before feeding	318.76	351.55	294.27	343.57	27.15
after feeding	474.08	495.78	437.81	484.32	35.51

Appendix 28. Analysis of variance for rumen pH, and VFA concentration Experiment 2.

Paramater	Source	Df	Type III SS	F Value	Pr > F
Rumen pH before feeding	TR	3	0.08127111	1.40	0.3206
	BL	1	0.04308477	2.22	0.1794
	BR	1	0.01040766	0.54	0.4873
	TR*BR	3	0.03935248	0.68	0.5930
	TR*BL	3	0.13540339	2.33	0.1607
	BL*BR	1	0.01991842	1.03	0.3442
	TR*BL*BR	2	0.00883667	0.23	0.8017
	ERROR	7	0.13555000		
after feeding	TR	3	0.07030804	2.83	0.1164
	BL	1	0.01017785	1.23	0.3045
	BR	1	0.00961335	1.16	0.3173
	TR*BR	3	0.19722753	7.93	0.0118
	TR*BL	3	0.12628997	5.08	0.0354
	BL*BR	1	0.07876053	9.50	0.0178
	TR*BL*BR	2	0.01621542	0.98	0.4222
	ERROR	7	0.53903636		
Total VFA before feeding	TR	3	8645.30726263	0.72	0.5727
	BL	1	3738.22131068	0.93	0.3671
	BR	1	18372.79095021	4.57	0.0699
	TR*BR	3	11519.91079906	0.96	0.4648
	TR*BL	3	18105.54787249	1.50	0.2956
	BL*BR	1	4757.98800263	1.18	0.3127
	TR*BL*BR	2	15676.31418875	1.95	0.2123
	ERROR	7	28145.44565000		
Total VFA after feeding	TR	3	15168.08735011	0.73	0.5636
	BL	1	433.84440793	0.06	0.8089
	BR	1	1073.98755959	0.16	0.7045
	TR*BR	3	6650.41611005	0.32	0.8095
	TR*BL	3	3956.12011721	0.19	0.8988
	BL*BR	1	3965.76947368	0.58	0.4725
	TR*BL*BR	2	4737.13231875	0.34	0.7201
	ERROR	7	48158.98900001		

VFA=Volatile fatty acid, TR= treatment, BR= breed, BL=block

Appendix 29. Analysis of variance for rumen ammonia and plasma ammonia concentration. Experiment 2.

Parameter	Source	Df	Type III SS	F Value	Pr > F
Rumen ammonia before feeding	TR	3	11.76303962	0.79	0.5361
	BL	1	25.70601636	5.19	0.0568
	BR	1	10.88062816	2.20	0.1819
	TR*BR	3	21.79094495	1.47	0.3039
	TR*BL	3	4.47943618	0.30	0.8237
	BL*BR	1	13.71602368	2.77	0.1401
	TR*BL*BR	2	0.60713667	0.06	0.9411
	ERROR	7	34.67910000		
after feeding	TR	3	207.24605485	0.85	0.5093
	BL	1	38.02691068	0.47	0.5160
	BR	1	0.81816448	0.01	0.9229
	TR*BR	3	107.81139267	0.44	0.7303
	TR*BL	3	780.18955623	3.20	0.0928
	BL*BR	1	37.30322368	0.46	0.5199
	TR*BL*BR	2	303.56413542	1.87	0.2239
	ERROR	7	569.01500000		
Plasma ammonia before feeding	TR	3	0.72317292	0.28	0.8353
	BL	1	0.04625208	0.05	0.8211
	BR	1	0.01801875	0.02	0.8877
	TR*BR	3	0.44232292	0.17	0.9110
	TR*BL	3	1.17808958	0.46	0.7156
	BL*BR	1	0.80341875	0.95	0.3587
	TR*BL*BR	3	1.15632292	0.45	0.7210
	ERROR	8	6.77725000		
after feeding	TR	3	24.60897934	72.37	0.0001
	BL	1	1.00808078	8.89	0.0246
	BR	1	4.05219393	35.75	0.0010
	TR*BR	3	2.81948695	8.29	0.0148
	TR*BL	3	6.41732898	18.87	0.0019
	BL*BR	1	7.10649000	62.70	0.0002
	TR*BL*BR	2	12.97084060	57.22	0.0001
	ERROR	6	49.60122857		