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PARTIAL REPLACEMENT OF FORAGE FIBER WITH NON-FORAGE FIBER IN RUMINANT RATION: A REVIEW

A. Nadeem and A. B. Sufyan

Institute of Animal Nutrition and Feed Technology, University of Agriculture, Faisalabad, Pakistan

INTRODUCTION

The most widely used expression of fiber contents in ruminant diets is neutral detergent fiber (NDF). The NDF is not a chemically pure entity, but it represents structural carbohydrate components of feed that commonly require chewing activity for particle size reduction and passage from rumen. The NDF seems to be more suitable for determining fiber requirements because the optimal fiber concentration resulting in maximum fat corrected milk (FCM) has been shown to be more consistent across forages for NDF than that of acid detergent fiber (ADF) (Mertens, 1994). That's why the fiber must be of proper quality and particle size to ensure maximum dry matter intake (Wangsness *et al.*, 1981), optimal chewing activity (Grant *et al.*, 1990), normal ruminal fermentation (Davis and Brown, 1970) and milk fat percentage (Van-Soest, 1963).

The formulation of diets based on NDF as a percentage of the ration dry matter (DM) has been recommended because of the positive relationship between NDF and rumen fill and the negative relationship between NDF and energy density (Mertens, 1994). Therefore, diets low in fiber and high in starch are fed to increase intake of energy but these diets increase the risk of ruminal acidosis (Krause *et al.*, 2002). Further, fiber digestion is greatly depressed when ruminal pH declines below 6.0 (Shiver *et al.*, 1986). Dairy diets can be balanced for NDF but sources of NDF vary in their chemical and physical properties. Feed byproducts high in NDF do not stimulate rumination and salivation as do coarsely chopped forages (Sarwar *et al.*, 1992).

Dairy cows require forage fiber in diets for maximum productivity. However, excess dietary forage fiber often limits voluntary feed intake because of physical fill in the rumen (Oba and Allen, 1999). Dairy ration should have a minimum of 25% NDF, 75% of which must come from forage to maintain normal ruminal functions, milk fat percentage, and over all animal health (NRC, 2001).

In developing countries, forage production is continuously being decreased because of enhanced allocation of land for grain production to feed the ever-increasing human population. Thus, the availability of good quality forage in sufficient amount is reducing. The most promising alternative to green fodder for dairy production in the country is the optimum usage of crop residues. Many chemicals like sodium hydroxide, urea and ammonia have been employed for the nutritional upgradation of wheat straw. Supplementation of these forage fibers with protein and energy sources can also be used for ruminants but this renders rations uneconomical for a common farmer.

The objective of this paper is to review the current knowledge of use of fiber in ruminant ration and effects of replacing forage fiber with non-forage fiber on ruminal fermentation, nutrient digestion and utilization, and production in dairy cows.

Dietary fiber

Dietary fiber plays a fundamental role in ruminants to maximize dry matter intake (DMI) and stimulate chewing activity and rumen fermentation. In particular, NDF is defined as "effective" when it ensures a good chewing activity, maintaining a satisfactory milk fat content and FCM yield (Grant, 1997). This role of fiber is strongly influenced by the dimensions of the feed particles and their retention time in the rumen (Woodford and Murphy, 1988). Recently, there has been increased interest in byproducts in partial substitution of traditional feedstuffs in ruminant feeding. From nutritional viewpoint, byproducts are included in the ration to supply energy and protein, but are often also characterized by high fiber content. The fiber of byproducts has different physical and chemical properties from forage NDF (Zhu *et al.*, 1997); in particular, its particles have small dimensions and a high density (Firkins and Eastridge, 1992).

However, many experiments have shown that a partial substitution of forage fiber with byproduct fiber in diet does not negatively affect rumen activity or milk fat content (Zhu *et al.*, 1997; Grant, 1997). Colenbrander *et al.* (1991) demonstrated that reducing the size of alfalfa silage particles decreased the chewing activity but did not change milk yield or composition. Sheep and goats are more likely to adapt the diets with a high content of low quality fiber; moreover, they seem to be less sensitive to the length of fiber particles (Lanza *et al.*, 1996; Sanz Sampelayo *et al.*, 1998). It has been shown that milk fat content is not necessarily decreased by a reduction of the dietary forage fiber

(Rapetti *et al*., 1995) or by the reduction of the fiber particle size (Sanz-Sampelayo *et al*., 1998). Reducing forage particle size increases forage DMI, particularly if forage quality is poor, due to a shorter retention time of the particles in the rumen (Woodford and Murphy, 1988), but simultaneously the higher turnover decreases the energy digestibility of the forage because of the lack of time available for fiber digestion.

Forage NDF

Forages, in spite of their low energy contents, are the major source of fiber. As genetic potential for milk production increases, provision of sufficient energy and fiber to the dairy cow becomes more difficult. NRC (2001) have recommended that 75% of the total dietary NDF should come from forages. Daily rumination time is directly proportional to NDF intake (Welch, 1982). The NDF is better related to intake and gastrointestinal fill than any other measure of fiber (Van-Soest, 1982). Thus, it is generally considered that the fiber requirement can be better expressed in term of NDF rather than ADF or crude fiber (Welch and Smith, 1969). Swain and Armentano (1994) suggested that non-forage fibers were approximately one-half as effective in providing physical characteristics of fiber as alfalfa silage when replaced in low fiber diets. Although NDF of any sort will satisfy the rumination requirement, the quality of that fiber has an important effect on the rumen environment and on microbial efficiency (Oke and Loerch, 1991).

Sarwar *et al*. (1992) replaced forage NDF with NDF from corn gluten feed and soybean hulls and reported that 60% NDF from forage was adequate to stimulate ruminal function and milk production when the total diet contained 31% NDF. Forage NDF as a percentage of total NDF may not adequately reflect the presence of effective fiber when feed by-products high in fiber are fed. So, when forage NDF is to be used as an index for adequate fiber, particle size and species of forage must be evaluated. Likewise, when forage portion of the diet is to be replaced with a more digestible source of carbohydrate, the concentration of non-forage NDF must be considered.

Non-forage NDF

Special attention to fiber levels should be given when balancing diets that contain a large proportion of non-forage NDF because of their low effective fiber contents. Firkins (1995) suggested that although the potentially fermentable fiber contents of many of these feeds were high, the rate of fiber digestion was slower than for most traditional forages. Secondly, the small particle size of many of these feeds and their high-density resulted in a fast rate of passage, thus decreased the time spent in the rumen. Thirdly, replacing forage NDF with non-forage NDF sources may have further negative associative effects with other feeds. For example, soyhulls have high fiber content but low in effective fiber, and thus they cannot be used to replace large portions of dietary forage (Grant, 1997).

Weidner and Grant (1994b) replaced silages with 25% of soyhulls in a dairy diet and found that soyhulls decreased the dietary particle size by 33%, resulting in reduced ruminating time by one-half and altered consistency of the ruminal mat. In another study, Weidner and Grant (1994a) substituted soyhulls at 15 and 25% for forage (alfalfa and corn silage 1:1), which comprised 60% of the control DM for cows in early and mid-lactation. Soyhulls substitutions reduced milk yield when coarsely chopped hay was added to the higher soyhulls diet. From this study, it was concluded that when high quality forage was limited, the percentage of forage NDF could be successfully reduced to 45% with the inclusion of 25% soyhulls and 20% coarsely chopped alfalfa hay in the diet for lactating dairy cows.

The maximum rate of inclusion of soyhulls for cows in mid to late lactation was about 20 to 25% of total ration DM. However, cows in early lactation should probably not be fed soyhulls (Grant, 1997). Out of non-forage fiber sources (NFFS) available for use in ruminant diets, most have effective fiber values less than 50% of their total NDF contents (Stern and Zeimer, 1993). One major exception was whole cottonseeds, which appeared to be relatively good source of effective fiber. Armentano and Clark (1992) reported that NDF in whole cottonseeds was equivalent to 1.23 times the NDF in alfalfa. Firkins (1995) reported that effective fiber value of whole cottonseeds was 85% (% of NDF) and suggested that forage NDF in a diet could actually be decreased if whole cottonseeds were included in the formulations.

Dry matter intake

DMI decreases linearly as the amount of forage NDF decreases. Woodford and Murphy (1988) demonstrated that as mean particle size in the diet was reduced by alfalfa pellets, rumination and chewing times were reduced. In addition, ruminal pH remained lower (< 6) with the pellet diet than with the diets with larger particle sizes, resulting in decreased DMI. Similarly, low forage diets with a high percentage of NDF from by-products might have increased ruminal fill, contributing to lower DMI (Mertens, 1980). However, ruminal fill was probably not a factor that contributed to the reduction in DMI because of the major decrease in DMI that occurred when forage NDF was reduced (Grant, 1997). This reduced DMI might have occurred due to lack of effective fiber to stimulate rumination and saliva production or by acid accumulation from rapid ruminal fermentation.

Particle size and forage species are variables that need careful evaluation in combination with concentration of forage NDF for determining adequacy of NDF in the diet Similarly, when by-product feed sources having high fiber are used to replace forages, major consideration is the potential for stimulating chewing activity and ruminal function (Harmison *et al.*, 1997). Mooney and Allen (1993) compared the effectiveness of the NDF in whole cottonseeds and in alfalfa silage. Two alfalfa silages with theoretical cut lengths of 4.8 and 9.5 mm were fed, and cottonseeds replaced either 0 or 27% of the alfalfa NDF. When whole cottonseeds were included in the ration, DMI increased. The calculated effective NDF of cottonseeds was 41 and 78% of the total NDF compared with the effective NDF of longer and shorter cut alfalfa silages, respectively.

NDF has been associated with the depression of digestibility with high intakes (Mertens, 1983). Mechanistic models used NDF to predict the energy content of forages and DMI for ruminants (Illius and Allen, 1994). Hoover (1986) reported a linear relationship between the percentage of NDF and DMI ($r^2 = 0.33$).

Passage rate

The competition between digestion and passage rate is important for non-forage fiber utilization because of the small particle size and the potential for rapid fermentation and increase in specific gravity (Weidner and Grant, 1994a). Nakamura and Owen (1989) reported that the fractional passage rate of SH increased by 8%, as the amount of SH in the diet increased from 50 to 95.3% of the concentrate mixture. According to their calculations (Nakamura and Owen, 1989), even an 8% increase in passage rate could considerably depress the extent of ruminal NDF digestion. Although some digestive compensation may occur in hindgut (Sarwar *et al.*, 1992), accelerated passage may have been the major factor contributing to the lower digestibility of NDF and ADF for the high soybean hull diet (Nakamura and Owen, 1989).

Rumen fill

Mertens (1987) proposed that NDF can be utilized as an index of the rumen fill capacity of forages in the diet. The concepts put forth by Mertens (1983) were that a diet of 35% NDF resulted maximum NDF intake, higher concentrations of NDF limited intake through rumen fill and for lower NDF intake, diets were limited by the energy requirements of the animal. Allen (1996) suggested that rations containing rapidly fermentable NDF require more ration NDF to stimulate rumination, chewing and saliva flow. The relationship among nonstructural carbohydrates, ruminally available starch, and NDF in the ration was considered critical in maintaining proper rumen function. According to Poore *et al.* (1991), ratio of forage NDF to ruminally degradable starch should be about 1:1 to avoid depression in fiber digestion and to maintain normal rumen function.

Particle size and chewing activity

Fiber stimulates chewing activity that is related to the physical characteristics of NDF (NRC, 2001). To ensure adequate fiber, the NRC (2001) recommends the concentration of total dietary NDF for lactating cows fed diets with alfalfa or corn silage as the predominate forage and dry corn grain be at least 25% of dietary DM. The recommendation also states that 19% of dietary DM should be NDF from forage. The minimum amount of total diet NDF can be adjusted upward as the amount of NDF from forage is reduced or as forage particle size is reduced. It was reported that as mean silage particle size decreased, chewing time declined due to a reduction in saliva production and its buffering action (Grant *et al.*, 1990). Similarly, reduction in forage particle size increased DMI and decreased DM digestibility and retention time of solids in the rumen (Jaster and Murphy, 1983). It was because smaller forage particles leave the rumen faster, which may account for both the increased DMI and the reduced digestibility. Beauchemin *et al.* (1994) reported that alfalfa silage chop length was less critical when total diet forage level was consistent with NRC (2001) recommendations.

Rumen pH

As mean silage particle size decreased, rumen pH declined due to a reduction in saliva production and its buffering action (Woodford and Murphy, 1988). Low ruminal pH was associated with suppression of milk fat synthesis, possibly due to the formation of trans-C18:1 fatty acids in the rumen as a result of incomplete biohydrogenation of unsaturated dietary fatty acids (Herrera Saldana *et al.*, 1990). To overcome this, more NDF must be added from non-forage feeds than that of forage to achieve the increase in fat test (Swain and Armentano, 1994). However, the NDF from most non-forage fiber did not stimulate chewing activity as effectively as did forage NDF (Clark and Armentano, 1997; Depies and Armentano; 1995). Decreased chewing activity, when non-forage fiber replaced forage, also decreased the flow of salivary buffer to the rumen, rumen pH and NDF degradation (Grant and Mertens, 1992).

Chewing activity and rumen pH of lactating cows decreased when soyhulls replaced 42% of dietary forage in a 59% forage diet and total NDF was increased from 28 to 34% of diet DM (Weidner and Grant, 1994b). Feeding sodium bicarbonate may be useful in increasing total tract NDF digestibility when cereal NFFS were a major component of low-forage diets. Sodium bicarbonate supplementation increased rumen pH at 12 h post-feeding and tended to increase total tract NDF digestibility when lactating cows were offered diets containing 38% NDF and 20% corn silage, 15% alfalfa and 20 % corn gluten feed (Firkins *et al.*, 1991).

Excessive starch fermentation in the rumen depressed fiber degradation through decreased pH (Poore et al. 1991) but starch alşo decreased NDF fermentation independently of rumen pH (Grant and Mertens, 1992). Diets formulated with high NDF levels from NFFS had lower starch than diets formulated to provide equal effective NDF from forage, therefore the direct negative effect of starch on fiber digestion should be less for these high NDF diets.

Lactation

The earliest and most extreme demonstration of forage replacement with NFFS for lactating dairy cows involved the complete replacement of a mixed diet with soybean flakes (Wagner et al., 1965). Three cows were switched from a ration of hay and concentrates to soybean flakes (steam-treated soybean hulls that had been flaked by rolling) as the sole feed. During a 4 week period, milk production declined from 11.7 to 7.9 kg/day, and feed intake declined from 15.2 to 10.2 kg/day; however, milk fat remained relatively unchanged (3.71 versus 3.63%).

When dietary NDF from forage was reduced to 60%, which was well below the NRC (2001) recommendation of 75%, it still provided sufficient effective fiber for FCM production that was similar, or superior, to that with high forage diets. In fact, the NDF from forage has been reduced to as little as 39% with no significant effect on NDF intake or FCM production (Cunningham *et al.*, 1993). All diets contained combinations of alfalfa hay or silage and corn silage that were replaced by NFFS. The NDF intake was 11.9% and FCM was 2.8% greater in cows fed low forage diets than those fed high forage diets. For diets containing NDF percentage from forage of 60-70%, the NDF intake averaged 0.8% less and FCM 0.1% less than those of the control diet. However, if NDF from forage was 40 to 50%, NDF intake averaged 22% and FCM 5.2% more than those of the control.

Mertens (1994) indicated that the maximum ration NDF for mid and late lactation cows was $1.2 \pm 0.1\%$ of body weight/day when intake was limited by rumen capacity. Mooney and Allen (1993) compared the effectiveness of the NDF in whole cottonseeds and in alfalfa silage. Two alfalfa silages with theoretical cut lengths of 4.8 and 9.5 mm were fed and cottonseeds replaced either 0 or 27% of the alfalfa NDF. When whole cottonseeds were included in the ration, milk production increased. Similarly, Nocek and Russell (1988) reported that milk production was maximized when the ratio of NSC to NDF was between 0.9 and 1.2. Combs (1992) reviewed nine experiments and concluded that 4% FCM production declined linearly at 0.44 kg per percentage unit increase in dietary NDF, primarily because intake of NDF increased as its proportion in the total mixed ration (TMR) increased. McQueen and Robinson (1993) reported that for dairy cows fed TMR ranging widely in ratios of alfalfa silage and barley concentrates milk production declined by 0.43 kg per percentage unit increase in dietary NDF.

Some studies (Beauchemin *et al.*, 1994; Depies and Armentano, 1995) have been conducted recently using milk fat percentage as an indicator for the effectiveness of fiber from various by-product feeds. They concluded that change in milk fat percentage was not always indicative of physical effectiveness of fibrous feedstuffs. Clark and Armentano (1993) found that the NDF in whole cottonseeds was 1.3 times as effective as the NDF from alfalfa silage. The effectiveness of NDF in distillers grains was approximately 0.9. Importantly, negative effective values can be obtained for byproduct feeds when ADF and NDF concentrations in the ration exceed NRC recommendations (Chase, 1994). Therefore, effective NDF values of a feed can vary depending on other ingredients in the diet and on the quality of the forage NDF that the feed is replacing. For cows late in lactation, producing 16 to 24 kg of FCM, NDF contents of 34 to 38% were suggested by Mertens (1987). The NRC (2001) recommends a minimum of 25% NDF for high producing cows in early lactation. Although fiber requirements as a percentage of DM decreased as production increased.

The maximum amount of non-forage fiber that can safely replace dietary forage for lactation is still not known. Studies designed to determine the effectiveness of NFFS (as judged by milk fat percentage) when replacing forage fiber (Clark and Armentano, 1993; Swain and Armentano, 1994) have utilized mid lactating cows. Early lactation cows may not tolerate the larger amount of NFFS because of their greater tendencies for lameness, abomasal displacement and other metabolic disorders (Clark and Armentano, 1993).

Conclusions

Dairy cattle require fiber to maintain normal rumen fermentation and function. Fiber consumed by the animal is mostly of forage origin. However, the use of byproducts may also be a valuable source of fiber. As rumen fermentation proceeds, organic acids are produced and pH perceptibly falls. It is generally understood that rumination of consumed fiber stimulates saliva secretion and is effective in maintaining a normal rumen environment. This role of fiber is strongly influenced by the dimensions of the feed particles and their retention time in the rumen. Recently, there has been increased interest in byproducts in partial substitution of traditional feedstuffs in ruminant feeding. From a nutritional point of view, byproducts are included in the ration to supply energy and protein, but are also characterized by high fiber content. The fiber of byproducts has different physical and chemical properties from forage NDF, in particular, its particles have small dimensions and a high density. However, many experiments have shown that a partial substitution in the diet of forage fiber with byproduct fiber does not negatively affect rumen activity or milk fat contents. Effect of feeding rations of different particle sizes on chewing activity and rumen fermentation is less understood but is needed for a more precise understanding of fiber requirements of dairy cows.

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