

# PHYSICALLY EFFECTIVE FIBER FOR DAIRY COWS: CURRENT PERSPECTIVES

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## INTRODUCTION

In 1997, a series of papers were published in the *Journal of Dairy Science* from a symposium entitled "Meeting the Fiber Requirements of Dairy Cows." In this symposium, the term physically effective NDF (peNDF) was first defined and a system for using peNDF in ration formulation was proposed (Mertens, 1997). Since then, this measurement has become widely used (and misused) in applied dairy nutrition. The purpose of this paper is to present some current perspectives on how peNDF is used in the field today, discuss current limitations in our ability to measure peNDF particularly on-farm, and challenges for measuring and using peNDF in the future.

## PHYSICALLY EFFECTIVE FIBER: BASIC CONCEPTS

Physically effective NDF is defined specifically as the fraction of fiber that stimulates chewing and contributes to the floating mat of large particles in the rumen (Mertens, 1997). The primary physical characteristic related to peNDF has been particle size of the forage or feed. Consequently, there has been considerable effort exerted to develop laboratory-based particle sizing techniques that would accurately predict animal chewing response. The earlier term, effective NDF (eNDF), referred to the total ability of a feed to replace forage in a diet and maintain milk fat percentage. Unfortunately, the terms eNDF and peNDF are still used interchangeably by some in the field that contributes to confusion when comparing these values among feeds across feed databases.

The concept of peNDF was proposed to be a measure that was more restrictive than effective NDF and would accurately predict the cow's chewing response to forage/feed particle size. The peNDF of a feed is the product of the NDF content multiplied by a physical effectiveness factor (pef). The pef ranges between 0 and 1 (not effective to 100% effective at stimulating chewing). Although the peNDF system resembles earlier indices such as roughage value index (Sudweeks et al., 1981) and fibrosity index (Sauvant et al., 1990), it differs importantly in that it is based on NDF content and the relative effectiveness of NDF in promoting chewing, rather than being expressed as minutes of chewing per kilogram of dry matter (Mertens, 1997). Chewing activity per unit of feed intake varies with animal breed, animal size, and feed intake level, but variation due to animal size and feed intake are minimized with unitless pef ratios. Consequently, peNDF values should be constants for a feed and are generally additive in a feed formulation system (Mertens, 1997).

## MEASUREMENT OF PHYSICALLY EFFECTIVE FIBER BY SIEVING

Chewing activity and associated responses are good biological measures of fiber effectiveness, but for a system to be applied there must be a useful feed evaluation procedure that can be routinely used in a laboratory (Mertens, 1997), or even on-farm in the case of peNDF. Several nutritional models that are currently used in the dairy industry (such as CPM-Dairy version 3) require peNDF as a key input for the model to predict lactational response. Consequently, measuring peNDF content of forages, feeds, and total mixed rations (TMR) in the laboratory or on-farm has become important to nutritionists and consultants. Mertens (1986) was the first to propose a system that combined particle size measurement in the laboratory with the NDF concentration of a feed. This approach assumed that only fiber contained in particles large enough to stimulate chewing will be effective and this approach ultimately led to the development of the peNDF system in 1997.

A key question then becomes: what is the critical particle size for passage from the rumen, and which fraction of particles remains in the rumen to stimulate chewing? Poppi et al. (1980) found that feed particles retained on a 1.18-mm sieve (with a wet sieving technique) had a high resistance to passage from the rumen of sheep. Figure 1 in this paper relates sieve aperture with cumulative percentage of dry matter retained and clearly shows a break point at the 1.18-mm sieve with only 1 to 3% of particles passing into the feces being greater than the 1.18-mm sieve. Mertens (1986) consequently adopted the 1.18-mm sieving approach to fractionate the larger feed particles requiring chewing to pass from the rumen, and this "1.18-mm fraction" has become the standard laboratory assessment for measuring pef for feeds using dry sieving techniques.

It is interesting to note, however, that several researchers have indicated that a larger critical size may be more appropriate for cattle. Dixon and Milligan (1981) observed that particles retained on sieves with apertures of 6.8, 4.9, 3.2, 2.0, 0.7, and 0.25 mm had ruminal passage rates of 0.0004, 0.010, 0.025, 0.041, 0.048, and 0.059/h which indicates that particles retained on sieves >3.2 mm passed out of the rumen more slowly. Recently, using dry sieving, Yang et al. (2001) showed that ruminal outflow rate of particles less than 1.18 mm averaged 5.57%/h compared with particles retained on a 3.35-mm sieve, which had an average outflow rate of only 1.75%/h. Cardoza and Mertens (1986) observed that feed particles retained on sieves with apertures >4.0 mm would be retained in the rumen of dairy cows and contribute to chewing activity. Most recently, Oshita et al. (2004) presented convincing evidence that the critical particle size for escape from the rumen of nonlactating dairy cows was in fact larger than the 1.18-mm sieving fraction proposed by Poppi et al. (1980) for sheep and closer to the size of particles retained on the 3.35-mm sieve.

Although the peNDF system has become firmly established using the 1.18-mm sieve to measure pef, it appears that the critical size for cattle is actually closer to a fraction of particles that would be retained on a 3.35-mm sieve. Another point to consider is the variability in particle size distributions (and hence pef) among forages fed to dairy cattle.

Figure 1 shows the cumulative percentage distribution of particles for a range of haycrop silages fed at the Miner Institute (2004; unpublished) and assessed by dry sieving. Note that the variability in particle distributions among samples is greater for the 3.35-mm versus the 1.18-mm sieve. A similar relationship occurs for a range of corn silage samples, grass silages, and particularly sorghum silage samples analyzed at Miner Institute. The pef for these forages ranged between 0.20 and 0.80 at the 3.35-mm sieve, but only between 0.70 and 0.95 at the 1.18-mm sieve. Another point to consider is that the plot lines for different samples cross (cumulative distribution plots are not parallel) resulting in different pef rankings for individual samples depending on whether the 1.18- or 3.35-mm sieve is used. Consequently, a 3.35-mm pef value would not always be indicative of a 1.18-mm pef value. If a purpose of measuring pef in the laboratory or on-farm is to separate forages and feeds based on variability in peNDF, then we should consider whether a system based on the 3.35-mm sieve would be more appropriate for predicting cattle chewing response. An important point to be made is that there is substantial variability among forages in pef measured by either sieving fraction and we cannot rely on tabulated values to accurately formulate diets for dairy cattle. Using CPM-Dairy version 3, adjusting the pef factors within the range that we observed in our sample set results in a change in metabolizable protein-allowable milk of over 2.5 to 3.0 kg/cow per day.

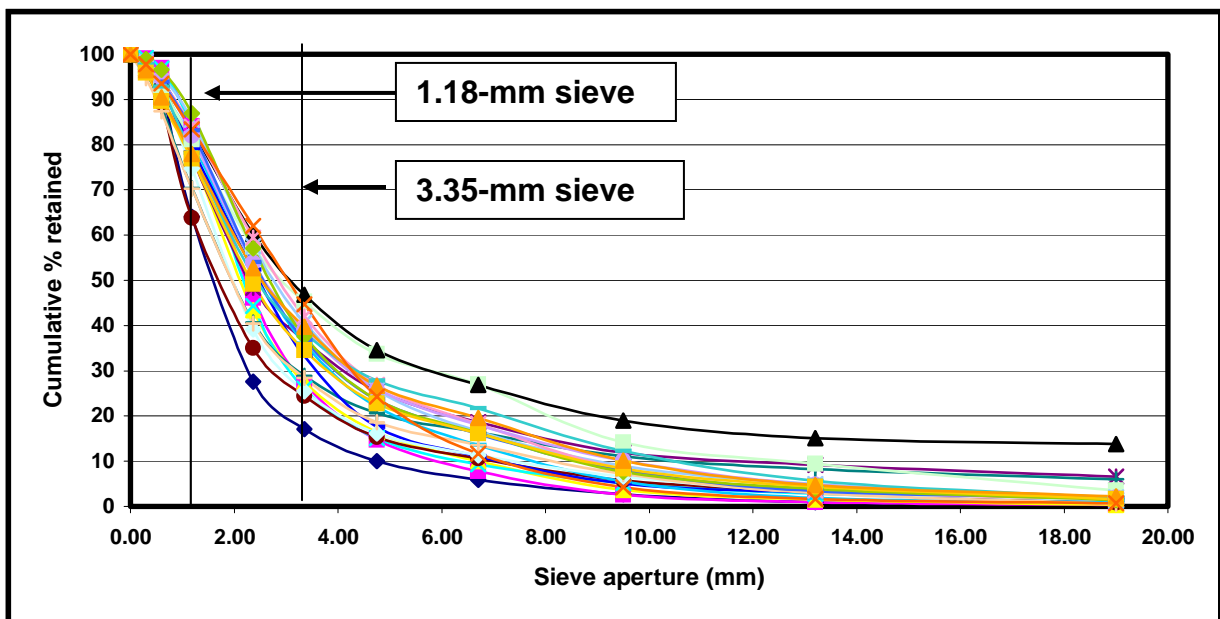


Figure 1. Cumulative percentage of particles retained for a wide range of haycrop silage samples at Miner Institute (2004). Samples were dry sieved using a vertical shaker (Ro-Tap shaker).

#### STANDARD PROCEDURE FOR MEASURING PHYSICALLY EFFECTIVE FIBER

The standard procedure for measuring peNDF involves use of dry sieving with vigorous vertical shaking using a Tyler Ro-Tap Shaker Model RX-29 (278 oscillations and 150 vertical taps/min). The standard method (Mertens, 2002) involves measuring

peNDF directly by determining the NDF in particles that pass through the 1.18-mm sieve and subtracting this amount from total sample NDF to obtain peNDF. A simpler approach was also proposed by Mertens (1997) and involves multiplying the proportion of particles (not the proportion of NDF) retained on the 1.18-mm sieve by the NDF content of the sample to obtain peNDF. This method is based on three assumptions: 1) NDF is uniformly distributed across all particle size fractions, 2) chewing activity elicited is similar for all particles retained on the 1.18-mm sieve, and 3) the fragility, or ease of particle size reduction during chewing, is similar among sources of NDF.

The first assumption may be valid, at least for some forage types and TMR, as shown in Table 1 (Miner Institute, 2004, unpublished). We compared pef measured as the proportion of particles retained on the 1.18-mm sieve (denoted as M1 in the table) or measured as the proportion of NDF retained on the 1.18-mm sieve (denoted as M2 in the table) for three sieving procedures: 1) standard dry sieving, 2) modified Penn State Particle Separator (PSPS) using the 1.18-mm screen, and 3) the PSPS combining the 19- and 8-mm screens as an estimate of pef. There were no large differences between the two methods of calculating a pef ratio and consequently a peNDF value. There were differences among the sieving procedures (standard dry sieving versus PSPS which will be discussed later).

Table 1. Comparison of two methods for calculating peNDF: M1) % of DM >1.18-mm x % NDF, or M2) % of sample NDF > 1.18 mm, for three sieving techniques.

Sample	Dry sieve		PSPS (1.18mm)		PSPS (19+8 mm)	
	M1	M2	M1	M2	M1	M2
Haycrop silage	34.4	32.9	40.6	41.7	30.3	31.1
Corn silage	34.7	32.0	39.3	36.7	29.9	29.4
TMR 1	27.4	27.3	32.7	34.9	21.9	25.8
TMR 2	25.3	26.3	31.7	32.8	22.4	24.7

The second assumption could be addressed by using additional sieves (for instance a 1.18- plus a 3.35-mm sieve) to better characterize the particle size distribution and relate chewing or other responses to each size fraction. The variability in particle distributions at each of these sieves as described earlier also supports the idea of evaluating peNDF using additional sieves (for example, the 3.35-mm sieve).

The third assumption that forages with the same pef may in fact elicit different chewing responses needs to be evaluated with further research. Mertens (1997) summarized research that showed the total chewing activity per kilogram of NDF for a range of long hays fed to cows varied between 111 min/kg of NDF for dried ryegrass to 209 min/kg of NDF for oat straw. This potentially variable chewing response to forages or diets with similar peNDF has important implications for nutritional models that incorporate peNDF and assume that every unit of peNDF is equal regardless of source. Earlier research (Winter and Collins, 1987) suggested measuring the grinding energy required to reduce particle size of the feed retained on the 1.18-mm sieve as a measure of fragility differences between feed sources with the same particle size. Other approaches could be developed and standardized that simulate chewing. A combination

of size fractionation plus a simple measure of fragility would offer a potential improvement to the peNDF system. This concept of combining fiber susceptibility to size reduction and particle size is critical. For example, the current feed dictionary for CPM Dairy version 3 contains instances where the pef value for two feeds are similar (based on particle size) when common experience indicates that substantial differences in chewing responses would be expected. One example would be ryegrass versus wheat straw: the dictionary contains a pef value of 100% for both roughage sources, but data summarized by Mertens (1997) shows that ryegrass elicits only 139 min of chewing per kilogram of NDF whereas straw elicits 209 minutes when both are fed as long hay to cows.

## ON-FARM ASSESSMENT OF PHYSICALLY EFFECTIVE FIBER

Currently, some commercial feed testing laboratories offer a dry sieving peNDF measure for samples, based on either the fraction of particles retained on the 1.18-mm sieve or the proportion of NDF retained on the 1.18-mm sieve. A common challenge for nutritionists and consultants is the on-farm measurement of peNDF. Currently, there is no on-farm tool that was designed specifically to measure pef or peNDF. A common tool employed to measure particle distributions of silages and TMR is the Penn State Particle Separator (PSPS; Lammers et al., 1996). This tool was developed for use on as-is samples on-farm to evaluate the particle size distributions and also to assess whether sorting has occurred. Unquestionably, the PSPS has revolutionized our ability to evaluate feed and ration particle distributions on-farm. It successfully mimicked results of the standard procedure S424 of the American Society of Agricultural Engineers (1993) for laboratory-scale measurement of particle size of chopped forages. The PSPS originally contained two screens (19 and 8 mm) plus a pan. Subsequently, the same research group published a set of standard operating techniques to improve the repeatability of the particle shaking technique, and also to insert a 1.18-mm screen to better fractionate the sample (Kononoff et al., 2003).

Although the major objective of the modified PSPS (with the 1.18-mm screen added) was to better fractionate smaller particles, especially for TMR, it has been used as an on-farm tool for measuring pef (% of particles > 1.18 mm, expressed on an as-is or DM basis). Several methods of using the PSPS as an on-farm tool for measuring peNDF have been proposed: 1) measuring the fraction of particles retained on the 1.18-mm screen (Kononoff et al., 2003), 2) combining the particles in the top two screens (19- and 8-mm screens) plus half the particles in the pan (or pan plus 1.18-mm screen for the modified separator), and 3) combining the particles retained on the top two screens (19 and 8 mm screens; Hutjens, 2001). Beauchemin and Yang (2003; 2005) have specifically proposed that peNDF can be measured using the PSPS by adding together the particles retained on the 19- and 8-mm screens or by using the 1.18-mm screen in the modified PSPS. These researchers do rightly caution that pef measured using different methods should not be directly compared when formulating or assessing diets and feeds. An important question is: how well does the PSPS actually measure pef for forages and TMR on-farm?

## PENN STATE PARTICLE SEPARATOR AND ON-FARM MEASUREMENT OF PHYSICALLY EFFECTIVE FIBER

Several studies using the PSPS to measure peNDF have been reported recently aimed at relating changes in peNDF with changes in feed intake, chewing, and ruminal pH of dairy cows (Yang et al., 2001; Krause et al., 2002; Beauchemin et al., 2003; Kononoff et al., 2003; Plaizier, 2004; Yang and Beauchemin, 2005 a,b). The results of these studies are conflicting. Variable relationships between peNDF and chewing activity and ruminal pH have been observed for corn silage- and alfalfa silage-based diets. In particular, some studies (Yang et al., 2001; Kononoff and Heinrichs, 2003a,b) showed that peNDF measured using the PSPS was a poor predictor of chewing time and(or) ruminal pH for cows fed corn silage- and alfalfa silage-based diets. Table 2 presents some data from Kononoff and Heinrichs (2003a) that illustrate the poor relationship between peNDF measured using the 1.18-mm screen of the PSPS and chewing and other animal responses to forage particle size. Clearly, the cows responded to particle size in this study (see Table 2), yet peNDF was consistently high and insensitive to marked changes in forage particle size as indicated by the percentage of particles retained on the 19-mm screen of the PSPS (which varied between 3 and 31.4%).

Table 2. Alfalfa silage particle size and lactating cow response (from Kononoff and Heinrichs, 2003a)

Item	Shorter	1/3L:2/3S	2/3L:1/3S	Longer
% of DM > 19 mm	3.0 <sup>a</sup>	12.3 <sup>b</sup>	21.9 <sup>c</sup>	31.4 <sup>d</sup>
peNDF, % of NDF	25.7	26.2	26.4	26.7
DMI, kg/d <sup>1</sup>	23.4	21.8	20.7	20.1
3.5% FCM, kg/d	35.6	35.0	34.5	35.5
Rumination time, min/d <sup>2</sup>	460	505	478	479
Ruminal pH <sup>2</sup>	6.04	6.15	6.13	6.09

<sup>abcd</sup> ( $P < 0.01$ ).

<sup>1</sup>Linear contrast ( $P < 0.01$ ).

<sup>2</sup>Quadratic effect ( $P < 0.02$ ).

Figures 2 and 3 show the relationship between peNDF measured using the PSPS (using both the 1.18-mm screen and the sum of the 19- and 8-mm screens as methods) and chewing time and ruminal pH. Across studies, there is no obvious relationship between peNDF assessed using the PSPS and chewing or ruminal pH.

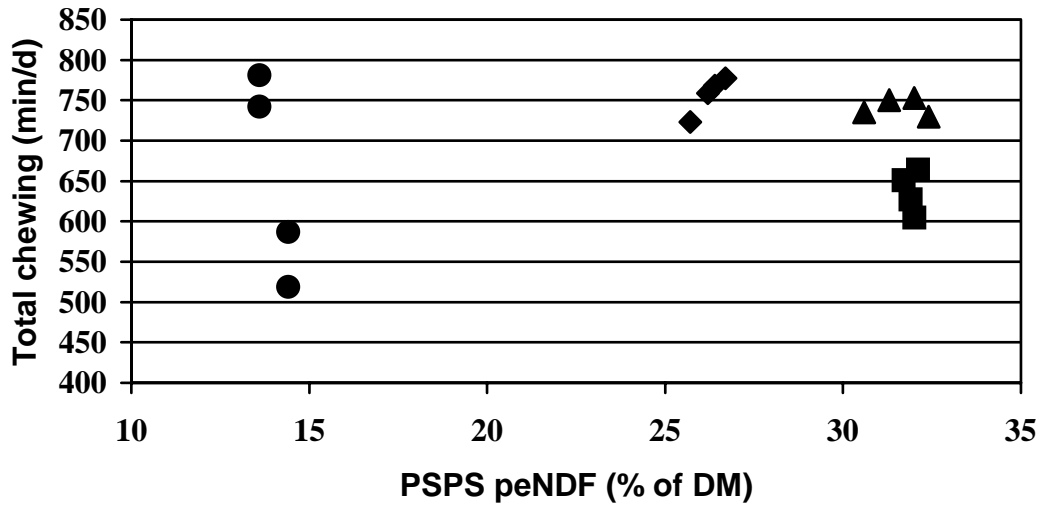


Figure 2. Relationship between peNDF measured using PPS and total chewing time for lactating dairy cattle. Different symbols represent four separate studies that made these measurements.

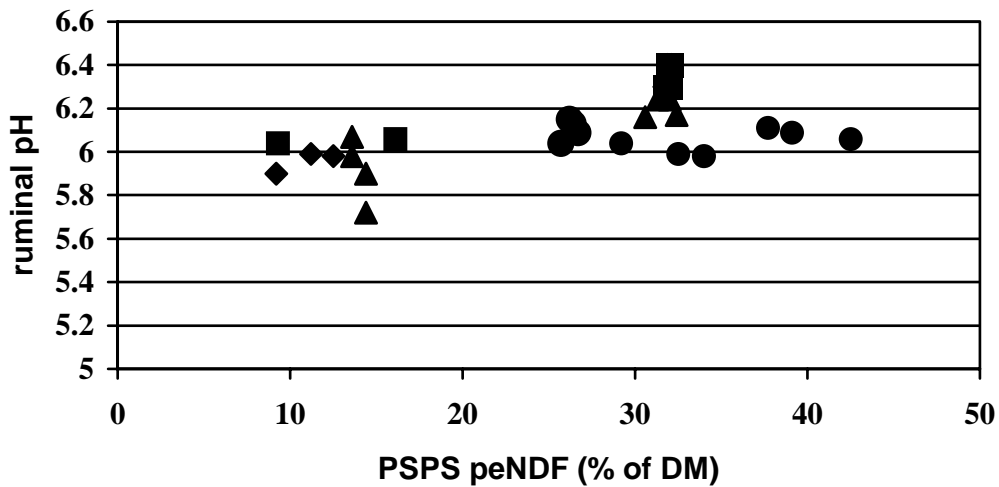


Figure 3. Relationship between peNDF measured using the PPS and average ruminal pH for lactating dairy cattle. Different symbols represent four separate studies that made these measurements.

Figure 4 shows the relationship between the standard dry sieving method for peNDF and the pef measured using the PPS for a range of haycrop silages (Cotanch et al., 2005). Similar results were observed for corn silage. Clearly, the PPS, using several common permutations of screens, does not agree very well with the standard dry

sieving method originally proposed for measuring peNDF (Mertens, 1997) that has been subsequently incorporated into nutritional models such as CPM-Dairy.

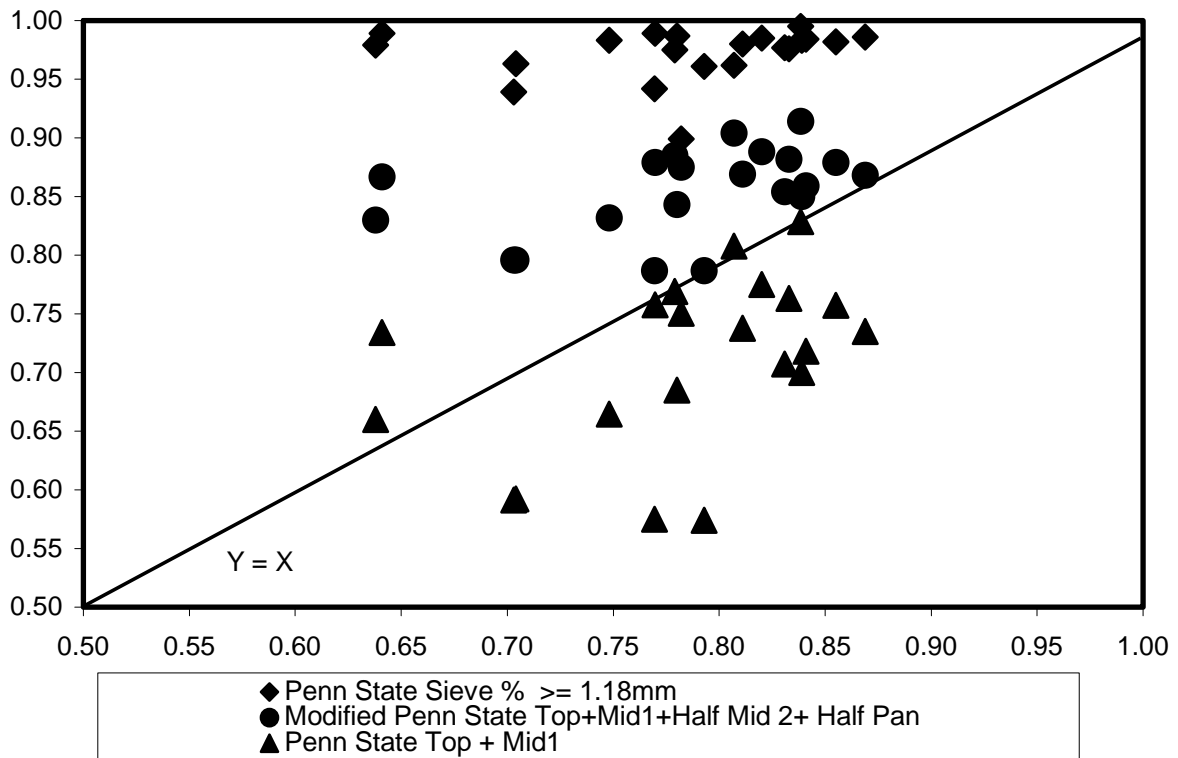


Figure 4. Relationship of standard dry sieving pef with pef determined using PPS with three techniques: 1) % particles >1.18 mm, 2) % particles retained on 19 and 8-mm screens + ½ of 1.18 and screen and pan, and 3) % particles on top two screens.

#### IMPLICATIONS FOR RATION FORMULATION AND ON-FARM ASSESSMENT

The peNDF system has become widely known and at least partially implemented within the dairy feeding industry since it was first developed in 1997. Some commonly used nutritional models use peNDF as a major input that drives model predictions of ruminal pH and microbial efficiency, and there is growing interest among nutritionists for not only laboratory measurement (dry sieving) of peNDF, but also on-farm measurement using as-is samples. Current feed libraries do not differentiate well among forages regarding pef. The PPS is a useful tool for evaluating particle size distributions of forages, TMR, and refusals on-farm for comparison to guidelines developed for the PPS. But, attempting to retroactively adapt the PPS as a tool for on-farm measurement of peNDF does not work predictably. The bottom line is that we are still looking for a tool to successfully measure peNDF on-farm – if we believe that such a tool would be useful in field application of the peNDF system. For those who desire an on-farm tool, it should provide pef values that agree well with the standard dry sieving method, and just as importantly, cow responses such as chewing. In the future, a



method of assessment that incorporates not only particle size, but also an easy and repeatable measure of fragility will be most useful for predicting cow response.

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