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Processing, Mixing, and Particle Size Reduction of Forages for Dairy Cattle¹

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ABSTRACT: Adequate forage amounts in both physical and chemical forms are necessary for proper ruminal function in dairy cows. Under conditions in which total amounts of forage or particle size of the forage are reduced, cows spend less time ruminating and have a decreased amount of buoyant digesta in the rumen. These factors reduce saliva production and allow ruminal pH to fall, depressing activity of cellulolytic bacteria and causing a prolonged period of low ruminal pH. Insufficient particle size of the diet decreases the ruminal acetate-to-propionate ratio and reduces ruminal pH. The mean particle size of the diet, the variation in particle size, and the amount of chemical fiber (i.e., NDF or ADF) are all nutritionally important for dairy cows. Defining amounts and physical characteristics of fiber is important in balancing dairy cattle diets. Because particle size plays such

an important role in digestion and animal performance, it must be an important consideration from harvest through feeding. Forages should not be reduced in particle size beyond what is necessary to achieve minimal storage losses and what can be accommodated by existing equipment. Forage and total mixed ration (TMR) particle sizes are potentially reduced in size by all phases of harvesting, storing, taking out of storage, mixing, and delivery of feed to the dairy cow. Mixing feed causes a reduction in size of all feed particles and is directly related to TMR mixing time; field studies show that the longest particles (> 27 mm) may be reduced in size by 50%. Forage and TMR particle size as fed to the cows should be periodically monitored to maintain adequate nutrition for the dairy cow.

Key Words: Forage, Feed Mixing

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Introduction

Silages have generally replaced long dry hay in diets fed in many of today's larger and more mechanized dairy farms. Improvements in the genetics, nutrition, and overall management of dairy cows have created the need for increasingly higher levels of dietary energy intake.

Forages alone cannot supply adequate DE for high-producing cows, and this has led to diets that are relatively high in concentrates (Smith and Pritchard, 1983). These nutrient-dense diets must be balanced for a variety of components, including several fiber fractions (NRC, 1989). Even though there is no specific long-fiber requirement for lactating dairy

cows, on many commercial dairy farms there is a managerial requirement for long dietary fiber. When minimum fiber levels are not met, cows often show one or more of a variety of metabolic disorders, including reduced total DM digestibility, reduced milkfat percentage, displaced abomasum, and an increase in the incidence of ruminal parakeratosis, laminitis, acidosis, and fat cow syndrome (Sudweeks et al., 1981). An important aspect of fiber nutrition is that cows that consume sufficient NDF but without adequate amounts of long chopped forage can also exhibit the same metabolic disorders as a diet deficient in fiber (Weston and Kennedy, 1984; Fahey and Berger, 1988).

Reduced forage particle size decreases the time spent chewing and causes a trend toward decreased ruminal pH (Woodford and Murphy, 1988). As particle length declines, cows spend less time chewing, thereby decreasing the volume of saliva produced that acts to buffer ruminal contents (Grant et al., 1990a,b). Sudweeks et al. (1981) developed a roughage value index system that estimates the chewing time of a diet using its mean particle size and DM and NDF levels.

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Forage Particle Size and Analysis

Insufficient particle size may decrease the ruminal acetate-to-propionate ratio and pH, which are often associated with low milkfat percentage (Santini et al., 1983; Woodford et al., 1986; Grant et al., 1990a; Shaver, 1990). When ruminal pH falls below 6.0, growth of the many fiber-digesting ruminal microorganisms is depressed, which allows for an increase in the propionate-producing microbes and a decrease in the acetate-to-propionate ratio (Grant et al., 1990a).

Reduced particle size of the dietary forage may increase DMI, decrease digestibility, and shorten rumen solids retention time (Jaster and Murphy, 1983; Martz and Belyea, 1986; Uden, 1987). Diets with smaller forage particle size contain feed particles that enter the rumen at a smaller size after initial chewing and swallowing and, therefore, leave the rumen at a faster rate. The result is an increase in the rumen particulate turnover rate, allowing for an increase in DMI (Jaster and Murphy, 1983; Martz and Belyea, 1986). Smaller forage particles spend less time in the rumen and are less available for microbial digestion; this decreases digestibility, particularly of fiber because of the relatively slow rate of digestion (Uden, 1987). In addition, the efficiency of ruminal microbial protein synthesis increases as forage size decreases, perhaps because of increased ruminal passage of solids; however, there is a reduction in net yield of ruminal microbial protein (Rode et al., 1985; Uden, 1987). Specific gravity, which is related to the density and buoyancy of particles, also plays an important role in influencing rates at which feed particles pass out of the rumen (Welch, 1990).

Cows normally consume particles of many different sizes. This, along with feeding frequency and the amount eaten, can allow for a more steady rate of digestion in the rumen and passage of digesta out of the rumen. The mean particle size and the variation in particle size are important nutritionally to the cow (Van Soest, 1982). Because the distribution of particle size is important to the animal, a description of the distribution of the length of feed particles (rather than only the mean) is needed for proper nutritional management (Mertens et al., 1984).

Forage particle size analysis can be performed with a large, stationary laboratory device fitted with five screens with different aperture sizes and a bottom pan to separate particles into six unique fractions, according to ASAE (1993). A simplified model of this device has been developed (Lammers et al., 1996a), with two screens and a bottom pan. This separator can be used on the farm by nutritionists and farmers to evaluate forage and total mixed ration (TMR) particle sizes.

The main goal in analyzing the particle size of the total ration is to measure the distribution of feed and forage particles that the cow actually consumes (Lammers et al., 1996a). When assessing the particle

length of a TMR, fresh samples should be taken from the feed bunk before the cows eat or sort the feed. The two-parameter Weibull distribution has been found adequate for plotting particle size distribution data (Pitt, 1987). Mixing and distribution equipment can reduce particle size of feeds and forages, and they need to be accounted for when evaluating the diet.

Particle Size Reduction

Because the particle size distribution is so important, we must understand how handling the crop from the time it is cut until it is placed in the feedbunk affects its particle size. Guidelines for theoretical length of cut (TLC) at harvest are poorly defined, and the resultant length of cut can vary owing to factors other than machine settings, such as crop moisture, sward thickness, and other mechanical factors (Savoie et al., 1989). Compared with horizontal silos, vertical silos generally require finely chopped forage to facilitate pneumatic conveyance and provide more compacting of material to exclude entrapped air. Horizontal silos have allowed the use of forages that are chopped longer and have a higher moisture content than forages used in conventional vertical silos (Savoie et al., 1989). However, forage particle size should not be reduced beyond what is necessary for proper compaction, ensiling, and mixing of the crop into a TMR. In addition, all movements of the silage or forage material will reduce particle size further.

There are a variety of ways that forage particle size can be reduced in silage making and feeding processes. Reduction can be attributed to the field harvester, the unloader and blower for tower silos, the silo unloader or unloading process, the TMR mixer, and finally the feed delivery system. Even though farm and feeding management practices can limit this reduction, all of these processes cause some degree of particle size reduction.

It is generally agreed that finely chopped silage requires more energy to harvest than coarsely chopped material (Evans et al., 1973). Under field conditions, this is not necessarily large (Ward et al., 1985). However, actual energy savings are influenced by equipment operating speed, crop yield, and crop moisture content (Savoie et al., 1989).

Pitt (1987) also found that the relationship between the median particle size after chopping and TLC varies with the mean initial forage particle length. For forages with short lengths, the median final chop length will greatly exceed the TLC; the median particle chop length is nearly equal to the TLC when the chop length is .7 times the mean initial forage length. The variability of forage particle size after chopping increases slightly with the variability in initial forage particle size and decreases with increasing leaf fractions of the initial plant material.

Evaluation of the Particle Size of Forages and TMR

In an attempt to better characterize the particle size of forages and TMR fed to cows, a large data set of forage and TMR particle sizes used by farmers in the Mid-Atlantic region of the United States was developed. In a cooperative effort with Cumberland Valley Analytical Services (Hagerstown, MD) and Pennsylvania State University, various forages and TMR samples ($n = 12,920$) were analyzed for chemical composition and particle length with the Penn State separator (Lammers et al., 1996b).

Particle size analysis for these data show that the mean percentage by weight of particles in grasses, legumes, and mixtures that exceed 19 mm in length are typically 16 to 18.4% (Table 1). Small grain silages had a slightly lower mean percentage of particles > 19 mm, whereas the percentage for corn silages was approximately 50% of that for legume and grass silages and is therefore chopped quite small. In the TMR samples, typically only 7.1% of the particles were greater than 19 mm. These data show the high variation of particles greater than 19 mm. The minimum and maximum values for samples with particles on the top screen ranged from 1.1 to 86.9%.

The mean percentage of particles between 19 and 8 mm in length ranged from 35 to 51% across all samples (Table 1). Corn silage samples had a high percentage of particles recovered on the lower screen (> 8 mm), where most of the grain was found. The standard deviation of particle retention for this fraction was one-third to one-fourth the size of the mean values, indicating less relative variability than for particles found on the top screen. In general, farmers chop corn silage more finely than other

forages, to increase silage compaction, to crack the kernels for improved digestion, and to reduce cob and stalk refusals in the feed bunk.

Particles < 8 mm length are nutritionally important because of relatively high surface area, which promotes rapid fermentation by ruminal bacteria and, therefore, generally yield more energy to the cow than longer particles (Uden, 1987). Mean percentages were nearly the same for all forage samples (i.e., 37 to 47%). The mean percentage of TMR particles in this fraction was 58%. As expected with TMR, the addition of processed corn, protein supplements, and minerals increased the percentage of particles < 8 mm. The variability in this fraction was similar to that for middle fraction. In general, there was a large degree of variability in forage and TMR particle sizes as fed.

It was considered to be of practical importance to determine whether NDF or ADF levels affected the quantity of particles greater than 19 mm. Correlations for the grass and legume silages were very low (Table 2), but, except with mixed, mostly grass samples, all were significant. The low correlations suggest that particle size cannot be used to predict ADF, NDF, or DM concentrations. Legumes with a low fiber level have a high leaf-to-stem ratio that allows for a high percentage of material (leaves) to fall through the top screen. Also, forage choppers, silo unloaders, and TMR mixers may reduce the particle size of forages low in NDF and ADF more than of ones high in NDF and ADF because a more immature plant contains less lignin. The low lignin levels of immature plants decrease structural strength, thereby reducing their shear strength. Lower NDF and ADF corn silage samples generally have a greater proportion of kernels less than 19 mm in size, which fall through the top screen. The correlations for TMR samples with the

Table 1. Mean percentages, standard deviations, and ranges of particles in three particle size fractions for a variety of samples

Sample	n	> 19 mm				8 to 19 mm				< 19 mm			
		\bar{X}	SD	Min ^a	Max ^b	\bar{X}	SD	Min	Max	\bar{X}	SD	Min	Max
%													
Grass	582	18.1	13.5	1.1	76.5	41.3	13.2	4.6	83.2	40.6	16.1	4.2	92.9
MMG ^c	280	18.4	13.4	1.1	78.5	38.4	12.0	.5	93.3	43.2	15.0	.0	91.6
M ^d	882	17.4	12.9	1.1	82.8	37.5	11.6	1.6	82.8	45.2	15.6	.2	95.4
MML ^e	1,606	16.4	12.3	1.1	86.0	37.2	10.8	.9	83.9	46.5	14.9	1.9	95.6
Legume	2,815	16.0	11.6	1.1	86.9	40.5	11.0	1.0	92.6	43.5	13.8	.0	96.1
SG ^f	529	14.6	9.4	1.2	61.6	48.4	13.9	11.8	89.5	37.0	16.3	2.6	83.7
CS ^g	5,395	8.1	6.4	1.1	81.6	50.8	12.3	.0	88.8	41.1	14.1	.4	96.9
TMR ^h	831	7.1	5.4	1.1	43.1	35.2	10.6	2.4	69.1	57.7	12.2	16.1	94.0

^aMin = minimum.

^bMax = maximum.

^cMMG = mixed, mostly grass.

^dM = mixed grass and legume.

^eMML = mixed, mostly legume.

^fSG = small grains.

^gCS = corn silage.

^hTMR = total mixed ration.

Table 2. Pearson correlation coefficients and *P*-values for percentages of NDF, ADF, and DM vs the percentage of particles greater than 19 mm

	% NDF		% ADF		% DM	
	r	<i>P</i>	r	<i>P</i>	r	<i>P</i>
Percentage greater than 19 mm						
Grass	.13	.002	.15	.001	-.12	.001
MMG ^a	.05	.19	.05	.23	-.21	.001
M ^b	.09	.006	.11	.002	-.26	.001
MML	.07	.003	.08	.002	-.31	.001
Legume	.06	.001	.05	.007	-.19	.001
SG ^d	.15	.001	.14	.001	-.01	.82
CS ^e	.21	.001	.19	.001	-.10	.001
TMR ^f	.23	.001	.27	.001	-.10	.005

^aMMG = mixed, mostly grass.

^bM = mixed grass and legume.

^cMML = mixed, mostly legume.

^dSG = small grains.

^eCS = corn silage.

^fTMR = total mixed ration.

fiber fractions are most likely due to a number of factors, such as the effects of the forage component being correlated, which typically makes up more than 50% of the TMR, and the other ingredients present in the TMR. Increasing the percentage of forage in the TMR would likely result in higher NDF and ADF levels and percentage of particles on the top screen.

All samples had negative correlations with DM concentration, which may be due to factors such as that, when forages are drier, the stems and leaves are more brittle and therefore subject to greater particle size reduction by forage harvesters and silo unloaders. Total mixed rations would exhibit the previously mentioned effect, as well as the influence of the percentage of forage in the TMR. Increasing the percentage of forage in the TMR would likely decrease the DM percentage and increase the quantity of particles on the top screen. However, the correlations for small grains, corn silage, and TMR samples were quite low and may not have any biological significance to the lactating cow.

TMR Mixing Time Study

Feed preparation may have large effects on forage particle size. An experiment to study the effects of mixing time on TMR particle size was designed using a four-auger Gehl (model 7500) mixer with a 2,720-kg capacity designed to handle up to 10% dry hay when operated at approximately 400 rpm. The mixer was filled to approximately 50% capacity with the two rations listed in Table 3. For each batch, replicate 15-L samples were taken from the mixer exit chute at 4, 8, 16, and 32 min after mixing began. The mixer fill order was the same for each replicate batch; corn silage, premix, high-moisture corn, alfalfa silage,

and then hay if appropriate. The mixer was not operated until after all ingredients were added.

Replicate samples of each ingredient were taken during filling for each batch tested. The long alfalfa hay was not sampled for particle size because particle size could not be measured without altering the distribution. All silage and TMR samples were analyzed for particle size distribution according to ASAE Standard S424 (ASAE, 1993).

Figure 1 illustrates the effect of mixing time on the quantity of particles longer than 18 mm for the batches without hay. If the mixer had no effect on particle size distribution, the fraction of TMR mass greater than 18 mm should have been 4.7%. As mixing time increased from 0 to 32 min, the fraction decreased to 1.6% (i.e., 66% reduction). Just 4 min of mixing reduced the mass of particles > 18 mm by 31%. Each experimental increase in mixing time (0 to 4, 4 to 8, 8 to 16, and 16 to 32 min) resulted in a lower fraction of particles longer than 18 mm ($P < .05$).

Figure 2 illustrates the effect of mixing time on the quantity of particles longer than 18 mm for the TMR mixes that included long hay. Each experimental increase in mixing time beyond 8 min (8 to 16 and 16 to 32 min) resulted in a lower fraction of particles longer than 18 mm ($P < .05$). It seems, based on the

Table 3. Target rations for controlled particle size study

Ingredient	Ration #1, kg	Ration #2, kg
Corn silage	925	910
Grain premix	180	180
High-moisture corn	140	140
Alfalfa silage	480	340
Alfalfa hay	0	180

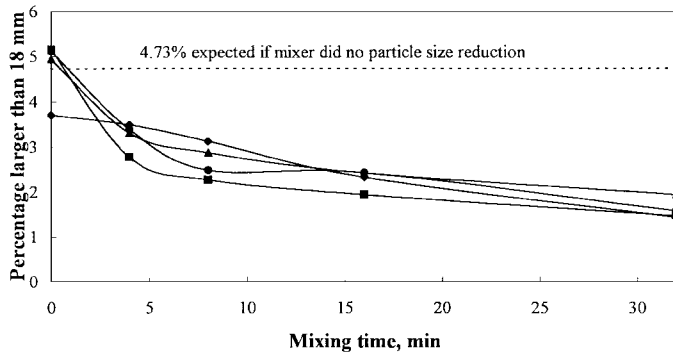


Figure 1. Effect of mixing time on fraction of sample mass consisting of particles longer than 18 mm (ration 1 in Table 1; no hay). Each curve represents a replicated batch.

apparent increase in mass of the long particle fraction, that the batches were not completely blended before 8 min and sample variation contributed greatly to uncertainty in sample particle size.

Figure 3 illustrates that, regardless of the particle size of interest, there was a trend toward a reduced longer particle fraction as mixing time increased. These data suggest that mixing can greatly reduce the size of the particles within the TMR.

TMR Field Study

To further study the effects of TMR mixing on particle size reduction, a larger study was designed. The extent of particle size reduction during TMR mixing under field conditions of normal preparation and delivery was studied on a convenience set of farms from west, southeast, and central Pennsylvania. Farms ($n = 23$) were selected based on the exclusive use of TMR for the lactating herd and not on the type of TMR mixer used. Nine of the samples included long

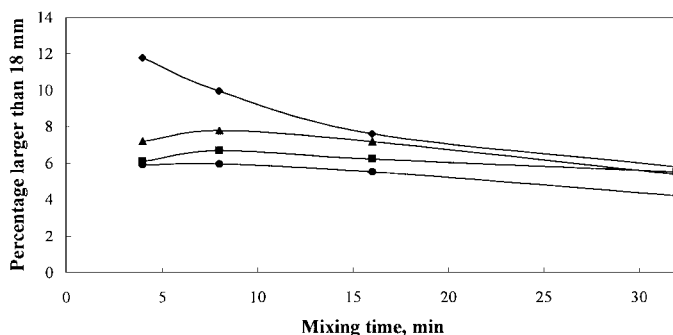


Figure 2. Effect of mixing time on fraction of sample mass consisting of particles longer than 18 mm (ration 2 in Table 1; with hay). Each curve represents a replicate batch.

dry hay added to the mixer. Four types of TMR mixers were used for a total of 25 individual diets. For each batch of TMR studied, all ingredient forages were sampled after unloading and immediately before TMR preparation. Replicate samples of these forages were measured for particle size using the device with five sieves (ASAE, 1993). Total mixed rations were prepared under normal farm conditions and usual procedures. Samples were taken from the feed bunk after mixing and delivery for analysis of particle size distribution. Based on the ration formulation and proportions of components in the ration, the expected particle size fractions were estimated from particle distribution data. Differences between the expected distribution of particles and the measured distribution were attributed to particle size reduction caused by mixing and delivery. The expected fractions of particles longer than 27 and 18 mm for the TMR samples

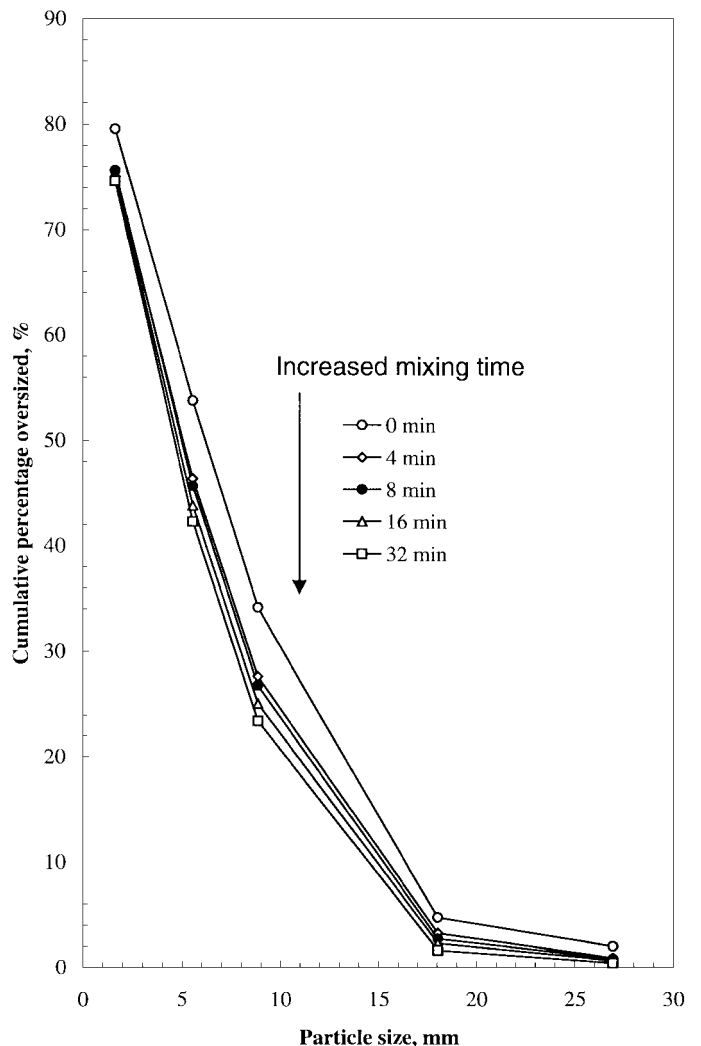


Figure 3. Percentage of total mixed ration sample mass longer than a particular size for the five particle sizes measured (ration 1 in Table 1; no hay). Each curve represents the average of four replicate batches.

Table 4. Percentage reduction in mass of total mixed ration particles > 27 and 18 mm for on-farm total mixed ration samples

Mixer type	With hay			Without hay			Overall		
	No. batches	Particles > 27 mm	Particles > 18 mm	No. batches	Particles > 27 mm	Particles > 18 mm	No. batches	Particles > 27 mm	Particles > 18 mm
	% reduction			% reduction			% reduction		
Auger	2	36	28.5	4	56	37	6	49	34
Chain and slat	2	17	2	7	40	2	9	35	2
Reel	4	32	7	2	70	35	6	44	16
Tumble	1	10	19	3	54	22	4	41	3
Overall	9	25	5	16	50	19	25	40	13

are given in Table 4. The range of 4 to 23% of particles longer than 18 mm is similar to data of Kammel and Leverich (1990) and previous data presented. Particle size distribution of hay was not determined; therefore, for batches that included hay, expected fractions of long particles were based solely on ensiled forages.

Results showed that for TMR that did not include hay, the fraction of particles > 27 mm was decreased by 50% and the fraction consisting of particles > 19 mm was decreased by 19% due to mixing and delivery. For batches in which hay was added, the reduction in long particles was lower. Hay was added to these rations in amounts that varied from .6 to 13.9% on an as-fed basis. The addition of hay resulted in amounts of long forage particles more similar to the expected amounts for the ensiled feeds alone; however, the additional long forage particles coming from the hay were not measured or added into the expected amount of long particles. Therefore, the addition of hay did not make up for the amount of particle size reduction caused by the mixer.

Implications

Particle size of forages varies greatly owing to factors involving the plant and the forage-harvesting and -storing equipment and procedures. Forages found on farms are often finely chopped, yet they conform to a Weibull distribution for particle size. Total mixed ration mixing and delivery systems produce dramatic decreases in particle size of ration components. Sampling of total mixed ration particle size must be done after mixing to determine the extent of long particle reduction that results from the feeding system on the farm.

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