ABSTRACT

Purpose: Our objective is to provide practical perspectives on how forage-fiber characteristics interact with feedbunk management to affect the balance between eating time and ruminating and resting activity. We offer recommendations for forage and dietary particle size to implement these concepts on farm.

Sources: Peer-reviewed scientific literature, research abstracts, and some proceedings and popular press were used to support our perspectives on this topic.

Synthesis: Chewing comprises eating and ruminating, which are complementary behaviors. Fiber plays a major role in stimulating chewing; source of fiber, dietary fiber content, degradability, fragility, and particle size influence its effect. The major role of forage particle size in many feeding situations is on eating rather than ruminating, since cows often chew feed to a relatively common particle size endpoint before swallowing, and the rumen is populated with a particle distribution that is more uniform than the diet. The time spent eating should fall typically between 3 and 5 h/d and needs to be in balance with recumbent rumination. Cows that accomplish more ruminating in stalls and lying down consume more dry matter and produce milk with greater fat and protein content. Diets that allow the cow to meet her time budget requirements contain >50% particles (as fed) on the 8-mm sieve of the Penn State Particle Separator and <5% on the 19-mm sieve to control sorting and eating time.

Conclusions and Applications: The length of cut for forages should be adjusted based on maturity and fiber degradability, fragility or susceptibility to breakdown, and moisture content for crops such as corn silage. As forages become more mature, lower in degradability, and less fragile, they should be chopped shorter to ensure optimal eating and ruminating responses. Similarly, immature or more fragile forages should be chopped longer. We propose recommendations for theoretical length of cut and ration particle size distribution that incorporate these concepts.

Key words: chewing, eating, recumbent rumination, particle size, time budget

INTRODUCTION

Eating and ruminating are central to the health, productivity, and well-being of dairy cattle. Chewing behavior, as the sum of eating and ruminating, must be optimized to manage the risk of rumen acidosis, enhance rumen fiber fermentation, and promote feed intake and ECM production. Figure 1 lays out a conceptual model of how forage and dietary characteristics, the management environment, and animal factors interact to determine the balance among eating, rumination, and resting. Successful dairy managers and consultants seek to optimize these dietary, management, and animal health factors that control chewing behavior.

We aim to provide perspective on how forage-fiber attributes such as rumen degradability, fragility, and particle size affect the balance between eating behavior and resting and rumination activity. We will present recommendations for forage and dietary particle size to take advantage of these nutritional and behavioral concepts on farm. We propose that the integrated effects of fiber content, degradability, and particle size on the balance of eating and ruminating time is essentially an overlooked, but crucial, component of forage and feed quality.

Eating and Ruminating Fundamentals

Eating time for lactating dairy cows averages about 4.7 h/d (range of 2.4 to 8.5 h/d) and ruminating time about 7.3 h/d (range of 3.9 to 10.2 h/d; White et al., 2017). Voluminous research, expertly reviewed by Beauchemin (2018), confirms the primary role of chewing during eating as initial particle size reduction and insalivation to lubricate the feed bolus and facilitate swallowing. Successive rounds of rumination contribute salivary buffering to the feed bolus and the rumen, facilitate particle size reduction
and passage, and promote greater surface area for microbial adherence and colonization.

Chewing behavior is controlled and modulated by a combination of animal factors, management environment, and physicochemical properties of the diet, particularly fiber. Although not a focus of this article, dietary starch affects the cow’s response to ration NDF and particle size (Grant, 2023). Dietary starch content and its degradability influence the minimum fiber requirement and need to be considered when formulating for NDF content and particle size (Grant, 2023). Eating time (min/d) is influenced by dietary NDF and forage NDF content, and the relationship strengthens when chewing time is expressed as minutes per kilogram of DMI (Beauchemin, 2018). Eating time is strongly and positively related to forage particle size over a range of diets and studies (Grant and Ferraretto, 2018), particularly the longer particles retained on the 19-mm sieve of the Penn State Particle Separator (PSPS; White et al., 2017).

Ruminating time is greatly affected by NDF intake, forage particle size, fragility (resistance of particles to breakdown during milling or chewing), and undegradable fiber (Grant, 2010; Cotanch et al., 2014). How quickly a forage particle breaks down during chewing is a function of exposure time to rumen fermentation, plant type (e.g., legumes and grasses, brown midrib and conventional corn), and relative undegradability of the NDF (Chap et al., 1984; Grant, 2010; Soufizadeh et al., 2018).

**Relationship Between Eating and Ruminating**

Beauchemin (2018) described the complementarity between eating and ruminating, with a change in one often balanced with an opposite change in the other. Dado and Allen (1994) fed cows a TMR containing 1:1 alfalfa and corn silages (58% of ration DM), in a noncompetitive tie-stall environment, and observed a strong negative relationship \( r = -0.62 \) between eating and ruminating time. Cows that spent less time eating ruminated longer. This response may be related to less particle size reduction of feed during rapid ingestion (Beauchemin, 2018; Weimer and Hall, 2020) and in some instances to time budget constraints as well. Grant and Ferraretto (2018) summarized research showing that cows fed higher-forage, longer particle-size diets tend to spend more time eating, borrowing time from resting behavior, whereas rumination time is less affected. Even if greater eating time does not come at the expense of ruminating time per se, longer eating times often reduce resting time, which has implications for rumination effectiveness, as explained later (McWilliams et al., 2021).

There is a biological maximum for total daily chewing time, and excessive time spent eating at high DMI may limit the time available for rumination (Beauchemin, 2018; Souza et al., 2022). Based on data summarized by Beauchemin (2018), maximum total chewing time for dairy cattle is approximately 16 h/d, although, on average, the on-farm maximum is likely closer to 12 h/d (i.e., 4.7 h/d eating + 7.3 h/d ruminating; White et al., 2017). Diets excessively high in forage NDF and coarse particles may elicit lengthened time at the feed bunk at the expense of resting and rumination time (Jiang et al., 2017; Grant and Ferraretto, 2018). In reality, animal and dietary factors set a maximum expected amount of rumination and eating activity, and we can only reduce that maximal amount with nonideal management (Grant and Dann, 2015).

---

**Figure 1.** Factors that influence chewing activity on farm. All factors interact as they determine the eating and ruminating behavior, and successful herd management will seek to optimize forage-fiber characteristics, ration formulation, management environment, and the health status of the cow.
RETHINKING THE ROLE OF FORAGE PARTICLE SIZE

Major Effect of Particle Size on Eating

Chewing response to particle size is mainly influenced by forage maturity, NDF degradability, and fragility. With many common forages such as corn and haycrop silages, increasing the particle size of the ration has a stronger effect on eating time than ruminating, indicating that considerable particle size reduction occurs during initial mastication during eating (Weimer and Hall, 2020). An exception may be cows grazing pasture or fed lush, vegetative grasses, where longer fibrous strands appear to be folded or balled into a bolus rather than cut before swallowing, and long vascular strands are observed in the rumen (Dineen et al., 2018). Digestive mastication of corn silage-based TMR differing in NDF degradability and chop length greatly reduces particle size before swallowing, and the degree of size reduction is greater for longer than for shorter silage (Fernandez and Michalet-Doreau, 2002; Fernandez et al., 2004). Despite a substantial range in NDF degradability and particle size of corn silage, only small differences were found in the particle size of feed that entered the rumen following eating and swallowing (Fernandez and Michalet-Doreau, 2002).

From a practical behavioral time budget perspective, dietary changes in NDF content, rumen NDF degradability, and particle size alter eating time by approximately ± 1 h/d (Grant and Ferraretto, 2018). Grant and Ferraretto (2018) documented greater eating time, with potential for lower DMI, with (1) greater dietary forage content for corn silage and haycrop silage; (2) lower NDF degradability for corn silage and sorghum silage; and (3) longer particle size for alfalfa silage, corn silage, and wheat straw. A simple substitution of brown midrib for conventional corn silage reduced eating time by about 30 min/d, presumably related to differences in NDF degradability and fragility (Miller et al., 2021). In these same studies, ruminating time was typically much less affected. Similarly, Haselmann et al. (2019) fed 80% forage diets comprised of grass hay and clover-grass silage processed such that either 73.5% or 23.0% (DM basis) of the particles were retained on the 19-mm sieve and either 21.5% or 63.2% of particles were retained on the 8- and 1.18-mm sieves of the PSPS. Eating time was reduced from 366 to 297 min/d as percentage of TMR on the 19-mm sieve decreased, with no significant effect on rumination time, which averaged 545 min/d. Importantly, even though eating decreased with the less coarsely chopped forage, DMI actually increased by 1.8 kg/d and ECM increased by 2.3 kg/d for these high-forage diets.

How Do Dairy Cows Chew?

“How Do Dairy Cows Chew?” is the title, in fact, of an insightful article published by Schadt et al. (2012), who assessed ryegrass hay of various particle distributions and NDF percentages, grass silage, corn silage, and TMR for the particle size reduction that occurs during eating. Despite a large range in mean particle size offered to the dairy cows in their study (9.7 to 43.5 mm), the size of the swallowed bolus during eating only ranged from 8.1 to 12.5 mm. Clearly, the size distribution became more uniform with ingestive chewing and reached a size similar to that of particles generally retained on the 8-mm sieve of the PSPS. This is a key point that we feel needs to be understood when assessing particle distributions in TMR fed to lactating dairy cows.

With coarser, drier, and higher-NDF feeds, cows chewed more per gram of NDF intake, such that the swallowed bolus particle size did not vary dramatically among feeds. Chews per gram of NDF ranged from 2.6 to 3.5 for the drier, coarser feeds down to <1 chew/g of NDF for the moist, finer-chopped feeds (Table 1). These results substantiate earlier work that has been generally overlooked by dairy nutritionists. Sheep fed fresh perennial ryegrass at immature and mature stages, fresh white clover, and chopped alfalfa hay chewed during eating until a common size end point was reached, and then the bolus was swallowed. For both sheep and dairy cattle, this chewing process presumably creates particles of proper size for swallowing, with sufficient saliva for lubrication of the bolus, greater particle surface area, and more rapid microbial colonization and fermentation (Ulyatt, 1982; Boudon et al., 2006). In addition to the greater eating time required with more ingestive chewing, there is also a larger energetic expenditure associated with greater eating activity (Weimer and Hall, 2020).

We have observed a 6-fold reduction in the longest particles of TMR before swallowing of a feed bolus during eating by lactating dairy cows. Particles retained on a 19-mm screen during wet sieving declined from 32 to 5% (DM basis) for a diet based on corn silage and chopped timothy hay containing 11.5% undegraded NDF at 240 h of in vitro fermentation (uNDF240) and 22% physically effective NDF (peNDF, measured using dry vertical sieving and 1.18-mm sieve; Smith and Watson, 2017). This diet lengthened eating time to 5 h/d compared with only 4.2 h/d for a diet containing 8.9% uNDF240, and it restricted DMI to 24.9 versus 27.5 kg/d for the lower-uNDF240 diet. By contrast, cows fed a high-uNDF240 diet with the same forage, but chopped finer, spent less time eating (4.6 h/d), had more frequent and shorter meals, and consumed more DM (27.4 kg/d; Smith et al., 2018).

To summarize, the dairy cow reduces ration particles to a rather uniform size despite a wide range of particles within the TMR. Cows will spend more time chewing while eating, and it may be incorrect to expect that longer particles in the TMR will elicit greater rumination. The bolus particle size for a variety of common forages and TMR falls within the range of approximately 8 to 11 mm when directly measured, as in Schadt et al. (2012). The ingestive chewing process is never 100%, and some larger particles are swallowed, so rumination can be affected, although to
a lesser extent than eating. In practice, we propose that it is easier to reduce rumination by feeding finely chopped forages than it is to boost rumination by feeding longer particles compared with an optimal peNDF diet.

**TIME BUDGET IMPLICATIONS FOR EATING AND RUMINATING BEHAVIOR**

Eating, resting, and ruminating are 3 key components of the dairy cow’s behavioral time budget. The proper balance between eating and resting, eating and ruminating, and resting and ruminating (i.e., recumbent rumination) is crucial to animal health, productivity, and well-being (Albright and Arave, 1997; Grant and Dann, 2015). The influence of dietary forage content and forage-fiber attributes on the balance between eating and ruminating is an overlooked component of forage quality.

Jiang et al. (2017) fed lactating dairy cows TMR containing a forage blend of primarily corn silage and alfalfa hay at either 40, 50, 60, or 70% of ration DM. As dietary forage percentage increased from 40 to 70%, NDF increased from 35 to 43%, peNDF increased from 15 to 29% (measured using the 4.0-mm PSPS sieve), and starch decreased from 30 to 20% (all as percent of DM). Because the researchers did not adjust the forages as dietary forage content increased, their diets addressed the question, “What happens to chewing and resting behavior when proper adjustments are not made for NDF content or characteristics?” Eating time increased by 107 min/d when dietary forage content increased from 40 to 70% (Table 2). In contrast, rumination time increased by only 35 min/d, resulting in an increase in total chewing time of 141 min/d as forage content increased from 40 to 70% of ration DM. Associated with these changes in chewing behavior as dietary forage content increased from 40 to 70%, saliva production during eating increased from 23.0 to 29.4% of total output, whereas ruminating saliva production was unchanged, and resting saliva production decreased from 42.7 to 32.9% of total. Importantly, resting time decreased by 141 min/d as forage content increased. Greater eating time required for the higher-forage diet came at the expense of resting time. The time budget implication is that the loss in resting exactly balanced the gain in total chewing time, driven by the need for cows to spend more time eating. Resting is fundamental to cow health and productivity, and dietary fiber characteristics and on-farm management should never force the cow to choose between eating and lying down.

Eating time between 3 and 5 h/d encourages natural feeding behavior (Grant and Albright, 2001) and rations or feed-bunk management that cause cows to spend more time eating will result in undesirable feeding behavior or limits to DMI and resting time, or both. Changes in forage NDF degradability and particle size have changed eating time by up to an hour (Grant and Ferraretto, 2018), and considering whether daily DMI targets can be met within 5 h/d should be an essential part of ration formulation. In the study by Jiang et al. (2017), eating time exceeded 5 h/d as ration forage content approached 60% or more of DM, emphasizing the importance of optimizing NDF characteristics for higher-forage diets.

**SIGNIFICANCE OF BALANCE BETWEEN EATING AND RECUMBENT RUMINATION**

The most effective rumination for the cow appears to occur while she is lying down, termed recumbent rumination, and we need to ensure that forages and feeding management allow the cow to balance eating time with time spent in recumbent rumination (Albright and Arave, 1997; McWilliams et al., 2021). In an ideal environment, 80% or more of the cow’s ruminating behavior occurs while she is lying down or sternally recumbent (Albright and Arave, 1997; Cooper et al., 2007). Potential benefits

<table>
<thead>
<tr>
<th>Item</th>
<th>NDF, % of DM</th>
<th>Feed particle size, mm</th>
<th>Bolus particle size, mm</th>
<th>Chews per gram of NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long ryegrass hay</td>
<td>57.1</td>
<td>—</td>
<td>10.3</td>
<td>2.6</td>
</tr>
<tr>
<td>50-mm rye hay</td>
<td>58.6</td>
<td>42.2</td>
<td>9.9</td>
<td>3.5</td>
</tr>
<tr>
<td>19-mm PSPS² rye hay</td>
<td>57.9</td>
<td>43.5</td>
<td>10.7</td>
<td>2.2</td>
</tr>
<tr>
<td>8-mm PSPS rye hay</td>
<td>59.1</td>
<td>25.1</td>
<td>10.8</td>
<td>1.7</td>
</tr>
<tr>
<td>1.18-mm PSPS rye hay</td>
<td>54.2</td>
<td>9.7</td>
<td>8.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Grass silage</td>
<td>53.1</td>
<td>13.8</td>
<td>11.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Corn silage</td>
<td>48.1</td>
<td>12.0</td>
<td>11.2</td>
<td>0.7</td>
</tr>
<tr>
<td>TMR</td>
<td>37.7</td>
<td>13.1</td>
<td>12.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

1Adapted from Schadt et al. (2012) and Grant and Ferraretto (2018, Copyright American Dairy Science Association, 2018).
2PSPS = Penn State Particle Separator.
of recumbent rumination include greater saliva secretion (Maekawa et al., 2002), physiological rest and rejuvenation (Ruckebusch, 1972; Ewbank, 1978), and greater protection afforded by rumination in a stall versus in an alley (Wierenga, 1990). Resting and rumination are important contributors to salivary buffer production (Maekawa et al., 2002), and so location and posture during rumination may affect volume or rate of salivary buffer production. For multiparous cows, salivation rate during resting may be affected by time available for resting versus eating (Maekawa et al., 2002). Management that reduces lying time will also reduce rumination. The cow’s preferred resting posture is sternal recumbency with left-side laterality (55 to 60% left-side preference; Grant et al., 1990; Albright and Arave, 1997). The combination of left-side laterality and upright posture is thought to optimize positioning of the rumen within the body for most efficient rumination (Albright and Arave, 1997).

Sleep time in cattle is relatively short, and rumination provides the physiological rest and rejuvenation provided by sleep (Ruckebusch, 1972; Ewbank, 1978). Electroencephalogram patterns recorded during rumination are similar to those of sleep or somnolence. Rumination is closely related to drowsiness and even occurs as the cow transitions into non-rapid eye movement sleep. It is conceivable that a behavioral continuum exists between rumination and sleep in ruminants. Cows can voluntarily control rumination, and, under acute and chronic stress, rumination will be depressed. Rumination is highly sensitive to cow well-being, and management factors such as overcrowding, poor bunk management, mixed-parity pens, excessive headlock time, and heat stress can reduce rumination by 10 to 20% or more (summarized in Grant and Dann, 2015).

Thus, there are several reasons why encouraging recumbent rumination would be beneficial to the cow’s rumen health and her overall well-being. Campbell (2017) and Campbell and Grant (2016) reported on how stocking density, dietary peNDF measured using dry vertical sieving and a 1.18-mm sieve, and feed restriction affected rumination and rumen pH of lactating dairy cows. Stocking density, varied between 100 and 140% of freestalls and headlocks, had an overall greater negative effect on rumen pH than did peNDF varied between 18 and 22.5% of ration DM. A combination of overcrowding and feed restriction for 5 h/d markedly increased the time when rumen pH was <5.8. However, under conditions of overcrowded stalls and feed bunks, Campbell (2017) observed fewer hours of rumen pH <5.8 when cows were able to achieve more of their rumination in a freestall, even though total rumination time was not affected by stocking density. As the fraction of the daily rumination time occurring within the freestall increased, time (h) of rumen pH <5.8 decreased (y = −20.7 + 21.1; R² = 0.44). Based on the positive relationship between rumen pH and greater milk de novo fatty acids (Fukumori et al., 2021) and total fat output, under competitive and overstocked conditions, cows able to ruminate more within a freestall should have better rumen conditions for fiber fermentation and potential for greater milk component output. In fact, McWilliams et al. (2021) observed that cows with greater ruminating time while lying down consumed more DM and produced milk with greater fat and protein content.

The healthiest and most productive cows effectively meet their needs for eating, resting, and ruminating. Cows that are not rushed while eating and that have the freedom to lie down and ruminate tend to have higher rumen pH. Avoiding rumen acidosis (i.e., low pH) promotes fiber degradation, microbial growth, and greater milk component production. We propose that not only do cows require sufficient time to practice natural eating and ruminating behavior, but that posture of rumination (i.e., recumbent versus standing) must be considered along with simply the daily time spent ruminating.

### IN VIVO CHEWING RESPONSES TO FORAGE NDF AND PARTICLE SIZE

A meta-analysis of 117 trials with 431 treatment comparisons conducted by Krentz et al. (2018) shed light on the relationships between chewing time and milk component output. Eating, ruminating, and total chewing times

<table>
<thead>
<tr>
<th>Item</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMI, kg/d</td>
<td>22.4</td>
<td>21.5</td>
<td>20.3</td>
<td>18.7</td>
<td>−3.7 kg/d</td>
</tr>
<tr>
<td>Eating, min/d</td>
<td>286</td>
<td>292</td>
<td>342</td>
<td>393</td>
<td>+107 min/d</td>
</tr>
<tr>
<td>Rumination, min/d</td>
<td>426</td>
<td>454</td>
<td>471</td>
<td>461</td>
<td>+35 min/d</td>
</tr>
<tr>
<td>Total chewing, min/d</td>
<td>712</td>
<td>745</td>
<td>813</td>
<td>853</td>
<td>+141 min/d</td>
</tr>
<tr>
<td>Resting, min/d</td>
<td>728</td>
<td>695</td>
<td>627</td>
<td>587</td>
<td>−141 min/d</td>
</tr>
</tbody>
</table>

1Adapted from data in the article by Jiang et al. (2017).
2All responses to diet were linear.
were positively related to dietary NDF and NDF from forage as a proxy for the physical nature of the NDF. As eating time increased, milk protein percentage, milk yield, and ECM yield declined. As rumination time increased, milk fat percentage and yield increased. Finally, as total chewing time increased, milk fat percentage increased, but milk yield was reduced. These results illustrate the sensitivity of productive responses to the relative balance of eating and ruminating activity.

In a recent study reported by Filho et al. (2022), the physical effectiveness of corn silage particles retained on the 19- and 8-mm PSPS sieves was assessed using lactating Holstein cows. Four different diets were fed: (1) a negative control with 17% forage NDF from corn silage, (2) 17% forage NDF plus 9% more NDF from finer corn silage particles that passed through the 8-mm sieve, (3) 17% forage NDF from corn silage plus 9% additional NDF from corn silage particles retained on the 8-mm sieve, and (4) 17% forage NDF from corn silage plus 9% NDF from silage particles retained on the 19-mm sieve. When cows were fed the diet containing supplemental fine corn silage, they chewed (eating plus ruminating) nearly 1 h less per day and yielded 6% less milk fat than cows fed the diet enriched with corn silage particles retained on the 8-mm sieve. This reduction in total chewing time and milk fat yield was predictable given what is known about the effect of smaller versus larger particles. However, cows fed the diet enriched with corn silage particles retained on the 8-mm sieve had greater DMI and about 1 h more chewing time per day than cows fed the diet containing corn silage retained on the 19-mm sieve. In this study the longest particles of corn silage did not stimulate the greatest chewing response. Additionally, cows fed the diet with more 8-mm particles produced 2 kg/d more milk and 8% greater milk fat. Similarly, in a study of 79 commercial herds in the Northeast and Upper Midwest that fed a wide range of TMR, herds with the highest milk fat percentage had >49.8% of TMR particles retained on the 8-mm sieve of the 19- and 8-mm PSPS sieves was assessed using lactating Holstein cows. Four different diets were fed: (1) a negative control with 17% forage NDF from corn silage, (2) 17% forage NDF plus 9% more NDF from finer corn silage particles that passed through the 8-mm sieve, (3) 17% forage NDF from corn silage plus 9% additional NDF from corn silage particles retained on the 8-mm sieve, and (4) 17% forage NDF from corn silage plus 9% NDF from silage particles retained on the 19-mm sieve. When cows were fed the diet containing supplemental fine corn silage, they chewed (eating plus ruminating) nearly 1 h less per day and yielded 6% less milk fat than cows fed the diet enriched with corn silage particles retained on the 8-mm sieve. This reduction in total chewing time and milk fat yield was predictable given what is known about the effect of smaller versus larger particles. However, cows fed the diet enriched with corn silage particles retained on the 8-mm sieve had greater DMI and about 1 h more chewing time per day than cows fed the diet containing corn silage retained on the 19-mm sieve. In this study the longest particles of corn silage did not stimulate the greatest chewing response. Additionally, cows fed the diet with more 8-mm particles produced 2 kg/d more milk and 8% greater milk fat. Similarly, in a study of 79 commercial herds in the Northeast and Upper Midwest that fed a wide range of TMR, herds with the highest milk fat percentage had >49.8% of TMR particles retained on the 8-mm sieve of the PSPS (McCarthy et al., 2018).

Filho et al. (2022) concluded that we need to focus primarily on the corn silage particles retained on the 8-mm sieve. Importantly, the NDF of corn silage particles retained on the 19-mm sieve was less effective at stimulating chewing than the corn silage particles on the 8-mm sieve due to sorting against longer particles. These in vivo results confirm that particles on the 19-mm sieve of the PSPS should be minimized and the focus placed on the 8-mm sieve, at least for corn silage-based TMR (McCarthy et al., 2018; Filho et al., 2022).

Cows fed in a competitive feeding environment practice more sorting (Albright and Arave, 1997) than cows in a noncompetitive environment. However, it seems clear that the fraction of TMR particle retained on the 19-mm sieve is most likely to be sorted in any feeding environment, in addition to boosting eating time (Kononoff and Heinrichs, 2003; Kononoff et al., 2003). In fact, the fraction of coarse particles retained on the 19-mm sieve, for a TMR based on corn silage and alfalfa hay, was predictive of coarse particles in the refused feed, but not of the proportion of cows ruminating 2 h following feeding, reflecting sorting and perhaps the time required for particle size reduction during eating (Melendez et al., 2002).

Overall, the research reviewed in this section provides compelling in vivo data to support revision of the PSPS recommendations for TMR (see below). We propose focusing on the particles retained on the 8-mm sieve when assessing TMR particle distribution to optimize the physical effectiveness of corn silage-based rations and minimizing particles retained on the 19-mm sieve to control sorting.

APPLICATIONS AND RECOMMENDATIONS

Particle Size Recommendations to Optimize Chewing Behavior

Recommended TMR particle distributions for the PSPS that seek to optimize the balance between eating and ruminating behavior are summarized in Table 3 (adapted from Cotanch, 2017). We emphasize that these recommendations reflect our current perspectives, and further research and field experience will be required for validation. Our recommendations are based on as-fed measures given the practicality of on-farm use of the PSPS. High-moisture forages may have different particle distributions on a DM versus as-fed basis.

Current recommendation provided by Penn State Extension for the 19-mm sieve is 2 to 8% of the TMR sample (DM basis; Heinrichs and Jones, 2016). Traditionally, it has been common to see 10 to 15% or even more of the TMR particles on this top sieve. Recently, a range of 4.2 to 55.5% of TMR particles on the 19-mm sieve has been reported for 72 dairy farms in the northeastern United States (Kerwin et al., 2023). In the absence of controlled research, but considering the in vivo data discussed earlier, we propose a target of 2 to 5% of the as-fed TMR sample. Rations with too much coarse material, especially if it exceeds 10% on the top sieve, encourage sorting and can extend eating time beyond the natural 3 to 5 h/d. This challenge becomes more difficult as forage content in the diet increases. These particles can be sorted and ideally most should not exceed approximately 2.5 to 5 cm in length. Shaver (2017) recommended a maximum of approximately 7.6 cm for particle length, referencing University of Wisconsin data that suggested that dairy cows most effectively sort particles longer than one-half the muzzle width.

The 8-mm sieve of the PSPS should be the focus to optimize eating, rumination, and cow productive response. These particles, although shorter than those retained on the 19-mm sieve, are effective. In fact, Filho et al. (2022) found that physical effectiveness factors (pef), based on animal responses such as chewing and milk fat percentage, were 0.44 for corn silage particles <8 mm, 0.75 for particles retained on the 19-mm sieve, and 1.0 for par-
articles retained on the 8-mm sieve. Particles retained on the 8-mm sieve range between 19 and 8 mm, as sieved, and theoretically average 13 mm, which is similar in size to the swallowed bolus while eating as measured by Schadt et al. (2012). Consequently, TMR containing approximately 50 to 60% of these particles should be more easily consumed by the cow within 3 to 5 h/d compared with coarser TMR.

The third, 4.0-mm sieve is often called the pef sieve. The pef is the fraction of forage or TMR particles that is coarse enough to stimulate chewing, and the pef is multiplied by the NDF content of the forage or TMR to obtain a peNDF value. Approximately 10 to 20% of the TMR should be retained on this pef sieve. Even though the particles are smaller, most are presumed effective at stimulating chewing, although that is an area requiring further research.

We propose that meeting the recommendations for these 2 sieves (2 to 5% for the top sieve and >50% for the second sieve) should translate into 3 to 5 h/d eating time and about 12 h/d resting time, with the majority of the approximately 7 to 8 h/d of ruminating occurring while the cow is lying down. That combination of chewing behaviors promotes greater DMI, higher rumen pH, and milk with greater fat and protein content according to research we have presented. We anticipate that future research and on-farm experiences will allow further development and adjustments to our recommendations.

**Recommendations for Forage Chop Length to Optimize Chewing**

The best recommendation to date for theoretical length of cut for various forages that allow adjustments based on fiber characteristics was recently developed by Woodley (2021). Figure 2 has been modified from the original article and shows that the recommended theoretical length of cut that optimizes DMI and rumen pH is a function of forage quality and NDF degradability, fragility, and moisture content, particularly for corn silage. This sliding scale for selecting the appropriate chop length recognizes the greater ease of fracturing for brittle legume particles versus grasses with their characteristic greater tensile strength (Chap et al., 1984). For some silages such as sorghum, the relationship between chop length and moisture content needs to be studied to ensure that nutritive value does not come at the expense of excessive silage leachate. The sliding scale of theoretical length of cut as a function of forage maturity depicted in Figure 2 can be usefully compared with a similar approach found in NASEM (2021; Figure 5-2). The NASEM (2021) figure presents a sliding scale for optimal dietary forage NDF content as a function of factors such as DMI, forage chop length, starch content and degradability, and feed-bunk management. In the future, quantitative data that improve our Figure 2 would also enhance the ability to implement the nutritional concepts in Figure 5-2 of NASEM (2021).

This approach to setting the length of cut attempts to integrate the nutritional concepts discussed in this article with the cow’s behavioral needs. For instance, more mature forages with greater unNDF240 will benefit from shorter chop length to maintain DMI. The balance between eating time and recumbent rumination ought to be sensitive and responsive to this range of theoretical chop lengths. In the future, this concept can be further developed with a combination of research and on-farm experience. Dietary starch content and degradability, source of NDF, and specifics of the feeding environment may all influence the optimal forage chop length. For now we propose these recommendations as a starting point for adjusting forage particle size as a function of fiber characteristics and corn silage moisture content that should be highly useful in the field.

**THE IDEAL ENVIRONMENT**

Forage quality and cow comfort must comprise a system. We need to target forage particle size, NDF degradability or fragility, and dietary forage percentage that allow the cow to consume her daily DMI within 3 to 5 h/d of eating time. We propose that this should be accomplished by

<p>| Table 3. Recommended TMR particle size recommendations using the Penn State Particle Separator (PSPS) to optimize balance between eating and recumbent rumination† |
|---------------------------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Sieve size, mm</th>
<th>PSPS 2013, % of DM</th>
<th>Miner 2017, % as fed</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>2–8</td>
<td>2–5</td>
<td>Sortable material; increases time needed for eating, especially if &gt;10%</td>
</tr>
<tr>
<td>8</td>
<td>30–50</td>
<td>&gt;50</td>
<td>Still physically effective, more so than 4-mm material; maximize amount on this sieve, 50 to 60%</td>
</tr>
<tr>
<td>4</td>
<td>10–20</td>
<td>10–20</td>
<td>Functions as physical effectiveness factor (pef) sieve; total of the top 3 sieves = pef</td>
</tr>
<tr>
<td>—</td>
<td>30–40</td>
<td>25–30</td>
<td>40 to 50% grain diet results in at least 25 to 30% in the pan</td>
</tr>
</tbody>
</table>

†Adapted from Cotanch (2017).
formulating rations with 50 to 60% of particles retained on the 8-mm sieve of the PSPS. These particles optimize eating time, DMI, and minimize sorting risk while effectively stimulating rumination. The other side of the equation is sufficient access to stalls and resting area to encourage recumbent rumination. A well-formulated, accessible TMR with appropriate particle size needs to be paired with comfortable stalls (or other resting resource) so that once cows are done eating, they can easily lie down and ruminate. In the dairy cow’s ideal environment 80% or more of daily rumination should occur while lying down. Recumbent rumination results in healthier rumen pH, greater DMI, and milk with greater milk fat and protein content. Although not a topic of this article, feed should be available ad libitum and pushed up within reach. Feeding frequency, feed push-up timing, and amount of feed refusals are all components of an optimized feeding environment.

Dairy managers, nutritionists, and crop personnel all must consider the time it takes for a cow to ingest the forage in her TMR and understand that eating, resting, and ruminating behaviors are biologically linked, and our nutritional and management systems must not unlink them. Forage fiber needs to be optimized within the TMR for efficient consumption, and then cow comfort must be optimized for the dairy cow to effectively process the swallowed feed via recumbent rumination.

We propose that using the recommendations for forage chop length and TMR particle distributions in this article will allow cows to extract the greatest nutritional value from their forages. Based on the reviewed research, time spent eating at the feed bunk can be considered an integral component of forage quality. Lower quality forage is less fermentable and takes longer to eat. Both have the potential to reduce energy intake, health, and productivity.

ACKNOWLEDGMENTS

The authors thank their collaborators at the William H. Miner Agricultural Research Institute and elsewhere. In particular, we thank the members of the “Informal Fiber Group” that has been meeting in conjunction with the Cornell Nutrition Conference since 2010. Many of the ideas presented here have been crystallized during countless hours of discussion within this group of scientists.

LITERATURE CITED


ORCIDs

R. J. Grant ● https://orcid.org/0000-0001-5797-9916
K. W. Cotanch ● https://orcid.org/0000-0002-1157-374X