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Review
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COMPREHENDING THE SIGNIFICANCE OF PHYSICALLY EFFECTIVE NEUTRAL DETERGENT FIBRE IN RUMINANT NUTRITION

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Abstract: As with all other species, the primary focus in the nutrition of ruminant animals is meeting animal's nutritional requirements. However, animal health, welfare, and metabolic status must be considered when meeting these needs. Therefore, understanding carbohydrate systems is crucial in ruminant nutrition. Starch, non-starch polysaccharides, sugars, and fibres are important carbohydrates in animal nutrition. Neutral detergent fibre (NDF), formed by cellulose, hemicellulose, and lignin, is primarily associated with dry matter intake. In addition, the concept of physically effective NDF (peNDF), which is related to total mixed ration particle size, is becoming quite widespread in ruminant feeding practice. The aim of this review is to discuss the effects of evaluating peNDF as a ration criterion in ruminant nutrition on dry matter intake, performance characteristics, rumen parameters, feeding behavior, and rumination.

Keywords: Dry matter intake, NDF, fibre, rumination, peNDF

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1. Introduction

One of the most critical aspects of feeding high-yielding dairy cows is ensuring they receive sufficient nutrients for milk production while maintaining healthy rumen function. For a healthy rumen, the dairy cow diet must contain adequate levels of physically effective long fibres. The physically effective neutral detergent fibre (peNDF) fraction in the diet increases saliva secretion and rumen buffering capacity by prolonging chewing and rumination time, and thus supports rumen pH stability (Allen, 1996; Beauchemin, 2018; Castelán Ortega et al., 2020). The physical properties of feed particles can have significant effects on dry matter intake (DMI), nutrient digestibility, milk yield and composition, and the overall health of the animal (Cao et al., 2021; Grant, 2023; Shi et al., 2023). Furthermore, the peNDF concept was introduced to explain the relationship between the physical properties of feeds and rumen pH, taking into account the effects of feed particle size on chewing behavior (Mertens, 1997). In this approach, peNDF combines the physical effectiveness factor (pef) and the neutral detergent fibre (NDF) content of the feed, providing a metric for determining the appropriate particle size in the diet (Yang and Beauchemin, 2005). The pef is calculated with the formula; DM retained on sieves > threshold / DM, where the threshold for the sieves is 1.18 mm, while peNDF= NDF (% of DM) × pef. The physical properties of feeds, especially particle size, affect digestibility, transit rate, and microbial protein production at both rumen and total digestive system levels. For example, microbial protein synthesis in the rumen has been reported to increase with increased nitrogen digestion in the total digestive system and increased feed particle length (FPL) (Yang et al., 2002). Furthermore, increasing the cutting length of forages may improve the digestibility of fibrous components within the total digestive system. Additionally, peNDF integrates the chemical properties of NDF, which are effective in rumen fermentation and maintaining acid-base balance, with structural properties such as particle size, and evaluates these two factors together (Tafaj et al., 2007).

The Penn State Particle Separator (PSPS), the most common field method for estimating the particle size of feeds and total mixed rations (TMR), is used to evaluate peNDF (Spina et al., 2024). The PSPS system consists of layers with screens measuring 19, 8, 4 and 1.18 mm in diameter from top to bottom, and different sources may recommend peNDF values based on different layers. Studies based on measurements obtained using PSPS, the most commonly used method, show that increased peNDF intake has positive effects on chewing time and rumen pH, increases overall digestibility (Yang and

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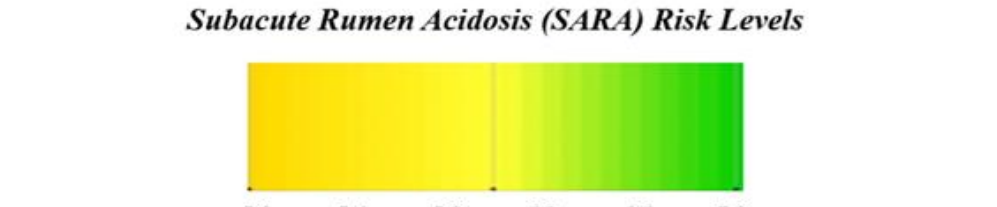
Beauchemin, 2005), increases in milk fat content (Kononoff and Heinrichs, 2003a). In contrast, some studies have reported that peNDF has no effect on digestibility or milk composition (Fernandez et al., 2004), whereas others have reported negative effects on digestibility (Kononoff and Heinrichs, 2003b).

In dairy cattle nutrition, high-energy diets are used to meet the needs of the animals and promote maximum milk production (Beauchemin and Yang, 2005; Zebeli et al., 2008a). Ensuring sufficient peNDF in the diets of high-yielding dairy cows is important for preventing subacute rumen acidosis (SARA) and the resulting decreases in milk fat, DMI, and fibre digestion, as well as the increased risk of lameness (NRC, 2001). SARA, a significant metabolic disorder in ruminant animal feeding practice, affects rumen function, productivity, and animal health in intensive milk production systems (Zebeli et al., 2008a). High concentrate feed intake increases the risk of SARA, which, although it does not produce significant clinical signs, can lead to decreased performance and is characterized by a moderate decrease in rumen pH (Plaizier et al., 2008; Zebeli et al., 2012). Indeed, the emergence of SARA is closely associated with the application of fibre-deficient but high-energy-starch diets and the inability to maintain rumen pH in the 5.5–7.0 range (Krause and Oetzel, 2006). SARA leads to various adverse consequences, including decreased DMI and fibre digestion, as well as abomasum displacement, diarrhoea, laminitis, and systemic inflammatory response (Plaizier et al., 2008).

Low ruminal pH and subsequent SARA are associated with the accumulation of volatile fatty acids (VFAs) because of rapid fermentation of readily fermentable carbohydrates in the rumen (Cao et al., 2021). Rumen VFAs can be removed by absorption through the rumen wall or buffered via saliva and dietary buffers (Li et al., 2014). A recent study showed that monounsaturated and branched-chain fatty acids in milk can serve as potential biomarkers for SARA determination (Fievez et al., 2012). These fatty acids are synthesized by rumen microorganisms and are highly sensitive to SARA conditions caused by high-grain-starch or low-peNDF rations (Khafipour et al., 2009). Although previous studies have examined the relationship between rumen pH and milk fatty acid levels in SARA conditions induced by starch-rich diets (Vlaeminck et al., 2006; Alzahal et al., 2010), data on SARA based on ration peNDF levels are still limited.

It is estimated that the saliva produced by a dairy cow can neutralize approximately 30–40% of the total VFA produced in the rumen (Allen, 1997). The particle size of the ration is one of the main factors affecting saliva production and is considered an important element in maintaining optimal rumen function and animal performance (Zebeli et al., 2012). In this context, sufficient peNDF intake can contribute to maintaining optimal rumen function; because large forage particles increase chewing time during both feeding and rumination, thereby increasing saliva production and promoting the formation of a network structure in the rumen (Mertens, 1997). The peNDF is related to the physical and chemical properties of the fibre, such as particle length, density, brittleness, moisture content, and digestibility; and together with NDF level and particle size, it plays a decisive role in chewing activity, rumen mat structure, and ruminal motility (Zebeli et al., 2012).

The use of high-energy diets in early lactation often leads to a decrease in dietary peNDF levels, which are necessary for healthy and proper rumen function. To reduce the risk of SARA, diets with high fermentation capacity should contain sufficient fibre. This relationship is schematically presented in Figure 1. To prevent SARA-related health problems, measures should be taken to prevent rumen pH from falling below <5.8 for more than 5–6 hours a day (Zebeli et al., 2012). Heinrichs (2013) reported that a particle length of 4 mm may be a more suitable threshold value in peNDF calculations.



Risk free (pH≥6.0)	Low risk (pH 5.8-6.0)	Moderate risk (pH 5.6-5.8)	High risk (pH<5.6)
peNDF ≥ 20% Starch≤ 20% Optimal rumen functions and microbial stability	peNDF 16-20% Starch 25-28% Optimal rumen functions and microbial stability	peNDF < 20 % Starch > 28 % SARA Decreased milk fat	peNDF< 16% High starch SARA Sharp decrease in milk fat Impairment of rumen function

Figure 1. Definition of Subacute Rumen Acidosis (SARA), diet peNDF and starch levels (Krause and Oetzel, 2006; Zebeli et al., 2012).

2. The Relationship between Dry Matter Intake and peNDF

Dry matter intake increases as the ratio of NDF and peNDF in the diet decreases, resulting in an increased rate of passage of digestive system contents into the digestive tract (Teimouri Yansari et al., 2004; Zebeli et al., 2008a). Conversely, excessive levels of peNDF can lead to decreased voluntary feed intake due to physical limitations caused by rumen fullness (Allen, 2000; Zebeli et al., 2010). Indeed, Zhao et al. (2011) reported that in dairy goats, increasing the peNDF8.0 content, a stricter version of physically effective fiber that only counts larger particles (> 8 mm) as physically effective, from 2.2% to 13.1% resulted in a linear decrease in DMI, with daily intake falling from 1.09 kg to 0.93 kg. Factors affecting DMI in ruminants are given in Table 1.

Some studies (Soita et al., 2005; Yang and Beauchemin, 2005) have shown that in dairy cows fed corn silage, particle size (between 9 and 19 mm) does not have a significant effect on DMI. However, other studies have reported a decrease in DMI in dairy cows when the total particle length of corn silage is increased. Schwab et al. (2002) found that increasing the total particle length of corn silage from 19 mm to 32 mm resulted in a decrease of 0.8 kg/day in DMI; however, they did not detect any increase in the residence time of digestive contents in the rumen. Moreover, recent studies have reported that increasing the peNDF level in the diet may lead to a decrease in dry matter (DM), crude protein (CP), and NDF digestibility in dairy cows (Molavian et al., 2020) and lambs (de Paula Carlis et al., 2021).

3. The Effect of peNDF on Feed Selection Behavior

Current studies show that peNDF has significant effects on DMI and particle separation behavior (Gentry et al., 2016; Llonch et al., 2020), ruminal pH level (Weiss et al., 2017), digestibility (Yang and Beauchemin, 2005), growth performance (Gentry et al., 2016), and carcass characteristics (Pereira et al., 2021a) in cattle. However, it is reported that the use of peNDF in feedlot diets is not widespread (Samuelson et al., 2016) and there is no clear consensus on optimal supplementation rates (Pereira et al., 2021b). Gentry et al. (2016) suggested that increasing feed particle size may limit feed selection behavior in cattle; they reported that the group fed with a ration containing 10.4% peNDF had the lowest level of selective picking behavior. When dairy cows were fed TMR, it was determined that the particle size of the feed had broader effects on animal performance, not limited to physical activity or the rate of fibre breakdown in the rumen (Tafaj et al., 2007). In a study, it was reported that moderately reducing particle size in the feed made the overall mixed ration more homogeneous, thereby reducing selective picking by animals before consuming the feed (Kononoff and Heinrichs, 2003b; Zebeli et al., 2008b; Alamouti et al., 2009). Reducing the breakdown of feed before consumption is associated with several positive outcomes, including a more regular circadian feeding rhythm in cattle, limiting daily DMI fluctuations (DeVries et al., 2005), and, most importantly, a reduced likelihood of rumen disorders even with a relatively high proportion of grains in the ration (Krause and Oetzel, 2006; DeVries et al., 2009). Circadian feeding in animals refers to the regulation of DMI, digestion, metabolism, and hormone secretion according to an approximately 24-hour biological rhythm.

4 Effects of Diet peNDF Level on Rumination and Performance of Ruminant Animals

The most fundamental characteristic that distinguishes ruminant animals from monogastric animals is their rumination behavior. The rumination process plays a significant role in stimulating digestion by facilitating the breakdown and digestion of feed material in ruminant animals. The emergence of rumination behavior follows a course parallel to that of rumen development during calf period (Xiao et al., 2024). Although the rumen is not yet fully developed in calves, it is reported that rumination behavior begins quite early, at approximately 1–2 weeks of age (Babu et al., 2004). Theoretically, an increase in rumination duration contributes to more efficient chewing of feed, reducing particle size and consequently increasing digestibility (Xiao et al., 2024). Rumination duration is also related to milk yield in dairy cows. Indeed, Codl et al. (2023) reported that milk yield increased due to the increase in rumination time.

Feeds with a long particle size increase rumination time and saliva production, contributing to the maintenance of the structural integrity of the ruminal mat (Pereira et al., 2023). Regulation of ruminal pH can reduce the risk of digestive system disorders such as SARA, as well as secondary complications such as lameness, rumenitis, liver abscesses, and systemic inflammation (NASEM, 2016). The fibre particles that make up the rumen mat play a critical role in maintaining rumen pH and function by physically stimulating rumination and saliva production.

Table 1. Factors affecting dry matter intake of ruminant animals (URL1)

Animal-based factors	Limiting factors	Environmental factors
Body weight	Diet NDF composition	Ambient temperature
Yield, physiological status	Diet energy content	Antinutritional factors of feeds
Body condition score	Ratio of diet protein to energy	Water requirements and intake

In conclusion, reducing the risk of SARA contributes to the protection of calf health, as well as improving growth performance (Khan et al., 2016; Xiao et al., 2020) and rumen development (Porter et al., 2007). Feeds with high physical fibre content have been reported to significantly increase rumen activity in adult dairy cows (Beauchemin, 2018).

Increasing the peNDF content in dairy cattle diets has positive effects on chewing behavior and rumen pH (Yang and Beauchemin, 2005). Krause et al. (2002) reported that increasing the pef of alfalfa silage from 0.31 to 0.69 increased the daily chewing time of cattle by 4.3 hours. Beauchemin et al. (2003) reported that linearly increasing the peNDF content from 7.2% to 15.0% in alfalfa-based diets improved both chewing activity and rumen pH in animals. Kononoff and Heinrichs (2003a) observed that increasing peNDF consumption in rations containing corn silage significantly increased chewing time per unit of dry matter and NDF. Table 2 presents the results of studies in the literature that examined the effects of different peNDF levels on rumination behavior and some performance characteristics in ruminant animals.

Forage sources form the cornerstone of nutrition in ruminant animals and have a significant impact on the healthy functioning of the rumen. The amount of forage added to animal diets is directly related to the animal's age, developmental stage, and production level. Forage includes structural carbohydrates such as cellulose, lignin, and hemicellulose, as well as non-structural carbohydrates such as organic acids and sugars. Various factors influence and promote the intake of carbohydrates in forage by ruminants.These factors are classified as animal-related (physical and physiological characteristics), feed-related (chemical composition, particle size, and vegetation period of the feed), and environmental factors (Wolfrum et al., 2009). Carbohydrates, milk fat, and milk components, which constitute a significant portion of ruminant diets, have a pronounced effect on the acetic acid/propionic acid ratio in the rumen, DMI, and rumen microflora and microfauna (Ferreira and Mertens, 2007; Saçaklı et al., 2007; Hansey et al., 2010).

Table 2. Effects of different peNDF levels on rumination and some performance characteristics in ruminant animals

Authors	Treatment	Findings
Wang et al., 2017	Ration peNDF at 10.8%, 13.5%, 18.0%, and 19.8%.	In diets prepared for 8-10 months old Holstein heifers, a peNDF ratio of 18.0% has been reported as at an appropriate level in terms of rumen pH, chewing activity, and nutrient digestibility.
Beauchemin and Yang, 2005	Ration peNDF at 8.9%, 10.3%, 11.5%	The study showed that increasing the peNDF ratio in dairy cow diets is associated with increased jaw movement, chewing time, and rumination behavior.
Cao et al., 2021	Ration peNDF at 9.0%, 10.6% and 11.3% ratios.	Increasing the peNDF level from 9.0% to 11.3% in the diets of dairy cows during the mid-lactation period has been reported to improve chewing and rumination behavior, balance rumen pH, and reduce the risk of SARA.
Tafaj et al., 2007	Ration peNDF at 19%, 24%, 28%, 32% and 39%.	The study showed that in dairy cows during the mid-lactation period, a peNDF ratio of 28-32% in their rations provides the minimum fibre level that positively affects chewing behavior and rumen health.
Zhou et al., 2022	Ration peNDF at 24.75%, 26.48%,28.14%,29.93%, and 32.97%.	In goat diets, a peNDF ratio of 28.14% has been reported to be an appropriate level in terms of digestion and rumen bacterial composition.
Yang and Beauchemin, 2006	Ration peNDF at 10.5%, 11.8%, and 13.8% ratios.	It has been reported that a peNDF ratio of 11.8% is sufficient to maintain optimum milk fat and milk yield in dairy cows during the mid-lactation period.
Li et al., 2014	Ration peNDF at 14.5%, 42.1%	In dairy goats, rations high in peNDF have been reported to support milk fat synthesis by increasing rumen pH and acetate production, while low peNDF levels are characterized by more intense fermentation in the rumen and consequently a lower pH.
Wang et al., 2011	Ration peNDF at 17.4%, 20.9%, 22.5%, and 25.4%.	Increased peNDF levels in goats significantly altered the physical particle composition of digestive contents in the rumen, duodenum, and ileum, while total nitrogen utilization, microbial protein production, amino acid profile, and blood biochemical parameters remained largely constant. The findings revealed that peNDF is primarily associated with mechanical digestion and rumination processes in goats.

Table 3. NDF and peNDF contents of some roughages used in the feeding of ruminant animals

Feed	DM, %	NDF, DM %	peNDF, DM %
Wheat straw	86.20	80.10	76.09
Corn silage	32.04	42.59	32.58
Alfalfa hay	90.39	41.11	38.94
Barley straw	87.80	76.80	72.48
Meadow grass	89.18	63.25	60.09
Alfalfa silage	44.41	53.50	44.93
Triticale silage	28.80	68.32	57.22
Dried vetch	90.29	53.69	44.78
Italian grass	89.39	57.97	51.27

DM= Dry matter, NDF= Neutral detergent fibre, peNDF= Physically effective NDF. The pef values required for calculating peNDF in the table above were taken from Mertens (1997), the NDF contents of the feeds were employed from NASEM (2021), and the peNDF values were calculated.

NDF is continuously needed to achieve maximum yield in ruminant animals and to maintain herd health. The rations of high-yielding animals should consist of roughage with appropriate particle size and optimal NDF content to support chewing activity, rumen fermentation, milk fat percentage, and adequate dry matter intake (Lean et al., 2007). Saliva production directly affects NDF utilization in relation to chewing time. Mertens (1997), in his analysis of 36 different studies, emphasized that chewing time is critical for maintaining milk fat percentage and reported that approximately 24 minutes of chewing time is necessary to obtain 2.9% milk fat per kg of dry matter. Recent studies have shown that peNDF is critically important for milk fat depression and animal health. Maintaining rumen pH and sustaining fermentation requires continued saliva production throughout feed intake, buffering the rumen and ensuring a healthy rumen environment (Lean et al., 2007). In contrast, peNDF relates to the total nutrient utilization capacity or the ability of a roughage ration to effectively maintain milk fat percentage in dairy cows. The NDF and peNDF1.18 contents of different roughages are summarized in Table 3.

5. Conclusion

Conceptually, NDF, which is related to feed intake, and its portion defined by TMR particle size, peNDF, is directly related to rumen pH, rumination, milk fat, feeding and feed selection behavior, and DMI in the nutrition of ruminant animals. Considering peNDF is extremely important in preventing metabolic disorders such as rumen acidosis and SARA, which are quite common in the nutrition of high-yielding ruminant animals. It has been reported that increasing the peNDF ratio in dairy cow diets increases jaw movement, chewing time, and rumination behavior. Due to its rumination-promoting properties, peNDF indirectly affects rumen buffering. Furthermore, the level of peNDF in the diet is critically important for managing the milk yield and feed selection process. Excessive peNDF levels can reduce voluntary feed intake due to rumen fullness. Therefore, peNDF, which has effects on rumen health, milk yield and quality, feeding behavior, and feed selection, should be considered a more frequently observed factor in ruminant diets. Although its use is becoming increasingly common in dairy cattle nutrition, studies are needed to determine the optimal peNDF levels for growth performance and rumen health in beef cattle and small ruminants, especially lambs.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	Ş.A.	A.A.	A.V.G.
C	50	25	25
D	75	25	
S		50	50
DAI	50	25	25
L	100		
W	75	25	
CR		50	50
SR	50	50	

C=Concept, D= design, S= supervision, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

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