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UTILIZATION OF PHYSICALLY EFFECTED FIBER (PEF) IN DAIRY COW

*** Oluwatoyin Osuolale**

Agricultural Research Station, Fort Valley State University, Fort Valley 31030, GA, USA.

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ABSTRACT

This review aims to provide a comprehensive understanding of the role of physically effective fiber (PEF), or peNDF, in the nutrition and rumen physiology of dairy cows. It investigates the physiological significance of fiber in dairy cow diets, stating its role in stimulating rumination, promoting saliva production, and maintaining optimal rumen pH. Factors influencing PEF requirements, including diet composition, feeding practices, and cow physiology, are thoroughly examined. Furthermore, the review discusses methods for measuring PEF and assessing its effectiveness in dairy diets, alongside the challenges associated with quantifying fiber effectiveness are addressed, shedding light on cases of fiber assessment in practical feeding scenarios. It investigates theeffects of PEF on rumen function, dairy cow performance, and the prevention of metabolic disorders such as subacute ruminal acidosis (SARA) providing insights into its crucial role in enhancing nutrient utilization, and overall animal health economic and environmental implications of formulating diets to meet PEF targets. It underscores the potential benefits for both farm profitability and environmental sustainability, emphasizing the significance of optimizing fiber levels to enhance nutrient utilization and minimize the environmental footprint of dairy production systems.

Keywords: Fiber, dairy cow, rumination, rumen pH, SARA.

INTRODUCTION

Fiber is a type of carbohydrate found in the cell walls of plants and is a "feed fractions that occupy space in the gastrointestinal tract and are indigestible and slowly digesting, or incompletely available" (Mertens *et al.,* 1992). fiber plays a crucial role in the animal's diet and overall health,In the diet of ruminant animals like dairy cows, fiber is essential for stimulating rumination (the process of chewing cud), which aids in saliva production and helps buffer the rumen's environment, maintaining a neutral pH necessary for the microorganisms in the rumen to function efficiently. These microorganisms break down the fiber into nutrients that the cow can then absorb and use for energy, growth, maintenance, and milk production.Fiber components are typically measured as **Neutral Detergent Fiber (NDF)** including cellulose, hemicellulose, and lignin, representing the plant material's cell wall portion. NDF is a good indicator of the feed's bulk and its ability to induce satiety in animals. **Acid Detergent Fiber (ADF)** consists of cellulose and lignin and is used to estimate the digestibility of the plant material. Generally, a lower ADF value indicates higher digestibility.

Physically effective fiber (PEF or peNDF) is a key component of dairy cow diets that plays a vital role in maintaining proper rumen function and overall animal health. PEF refers to the portion of forage in the diet that is effective in stimulating chewing and rumination, promoting saliva production, and facilitating rumen motility and stratification. These processes are crucial for buffering the rumen environment, enhancing nutrient absorption, and preventing metabolic disorders such as subacute ruminal acidosis (SARA). Achieving the right equilibrium between PEF and easily digestible carbohydrates in dairy cow diets presents challenges, yet it is essential for rumen functionality and overall metabolic health. As highlighted by (Plaizier *et al.,*2008), appropriate dietary balance is vital forsustainingproper rumen metabolism. Additionally, this balance significantly contributes to stable metabolic health and improved productivity in dairy cattle (Zebeli *et al.,*2011).

The concept of PEF is rooted in the physical characteristics of the feed, particularly its particle size and structure. The need for PEF arises from the cow's anatomical and physiological requirements; the rumen is a fermentation vat that works most efficiently when there is a balanced interaction between solid particles and microbial populations. Adequate PEF ensures that cows have enough fiber to chew, leading to the production of saliva, which contains bicarbonate acting as a natural buffer for the rumen fluid. Dairy cattle need feeds with appropriate particle sizes to support optimal rumen health. Ensuring the correct particle length is challenging because many commercial dairy feeds are rich in concentrates and premium silages, typically finely processed. Such diets are readily fermented in the rumen, promoting peak milk yield but may result in several metabolic issues. These include SARA, diminished fiber breakdown, decreased milk fat content, abomasa displacement, hoof problems, and fat cow syndrome (NRC 2000). Field Study conducted in the US, up to 19% of dairy cows in the early stages of lactation and 26% of cows in the middle of lactation have SARA (Garret *et al.,* 1997).The objective of this review is to elucidate the physiological significance of fiber in dairy cow diets, factors influencing PEF requirements, review methods for measuring PEF, and examine its effects on rumen function, cow performance, and metabolic disorders, the economic and environmental implications of formulating diets to meet PEF targets in dairy production systems.

Rumen Physiology

Dairy Cows can extract nutrients from high-fiber forage diets and convert them into products that are safe for human consumption and include premium proteins. Rumen is the primary site of fiber breakdown, mostly due to the activity of the microbiota, a diverse community of hundreds of species that includes bacteria, viruses, fungi, archaea, and protozoa. The bacteria living in the rumen encode

***Corresponding Author: Oluwatoyin Osuolale,**
Agricultural Research Station, Fort Valley State University, Fort Valley 31030, GA, USA.

a range of enzymes that break down the carbohydrates found in plant cell walls, enabling the animal host to obtain nutrients that would not otherwise be available. Because of the close, symbiotic link that has developed between Dairy cows and their microbiota over their shared evolution, we see them as holobionts (Muñoz-Tamayo *et al.,* 2023).

The rumen is the largest of the four compartments of a cow's stomach, followed by the reticulum, omasum, and abomasum. The rumen functions as a fermentation vat, where a diverse community of bacteria, protozoa, and fungi break down complex plant-based materials that are indigestible to many other animals (Hungate, 1966). This compartment has an extensive surface area, thanks to numerous papillae, which absorb volatile fatty acids (VFAs) produced during fermentation. These VFAs, including acetate, propionate, and butyrate, are primary energy sources for the cow. The rumen's anaerobic environment is ideal for the growth and activity of its microbiota, allowing for the breakdown of cellulose and hemicellulose into simpler compounds that can be further metabolized by the cow (Church, 1976).

Fiber, primarily found in the cell walls of plants, consists of cellulose, hemicellulose, and lignin. The digestion of fiber in the rumen begins with the mechanical breakdown of feed into smaller particles by chewing and rumination, which mixes the feed with saliva and introduces it to the microbial population in the rumen (Van Soest, 1994). Microorganisms attach to the fiber particles and secrete enzymes like cellulase, which breaks down cellulose into glucose units. Hemicellulose is similarly degraded to simpler sugars such as xylose and arabinose. These sugars are then fermented by other microbial species to produce VFAs (McDonald *et al.,* 2011). The efficiency of fiber digestion is influenced by several factors, including the physical characteristics of the feed, such as particle size, and the retention time in the rumen. Longer retention times generally allow for a more complete digestion of fibrous materials (Van Soest, 1994).The digestion of fiber in the rumen is critical for several reasons such as VFAs produced from fiber fermentation are a significant source of energy. For instance, acetate is crucial for fat synthesis, while propionate is vital for glucose production through gluconeogenesis (Church, 1976). Efficient fiber digestion increases the surface area for absorption and enhances the overall digestive capacity of the rumen. Adequate fiber stimulates rumination and saliva production, which helps to buffer the rumen environment and maintain a stable pH, crucial for microbial activity (Van Soest, 1994).

Factors Influencing PEF Requirement in Dairy Cow

Physical Effective Fiber (PEF) plays a crucial role in maintaining rumen health and function, influencing milk production and overall health in dairy cows.The requirement for PEF can vary based on several factors including the physiological state of the cow, the overall diet composition, and the management practices employed. The physiological state, including the stage of lactation, pregnancy, and age, significantly influences the PEF requirements of dairy cows. Lactating cows, especially those in early lactation, have high energy needs; thus, diets are often rich in concentrations to meet these demands. However, to avoid issues such as ruminal acidosis, sufficient PEF must be included to stimulate chewing and saliva production, which buffers the rumen pH (Allen, 2000). As the cow progresses through lactation, fiber requirements may decrease slightly as energy demands lessen. Pregnant cows and heifers may also have different fiber needs to support growth and fetal development (Grant and Albright, 2001).

The overall diet composition profoundly affects the PEF requirement. Diets high in rapidly fermentable carbohydrates (e.g., grains) increase the risk of ruminal acidosis, necessitating more PEF to maintain rumen health. Conversely, diets rich in forage may inherently satisfy PEF needs but can limit energy intake, which is critical for high-producing animals. Balancing the forage-to-concentrate ratio is thus essential for optimizing both energy intake and fiber effectiveness (Grant and Albright, 2001). The physical form of the diet, particularly the particle size of fiber, determines its effectiveness as PEF. Longer particle sizes generally increase chewing activity and saliva production, thereby enhancing rumen buffering. The Penn State Particle Separator is a tool commonly used to assess the adequacy of particle size in dairy rations to ensure optimal rumen function and prevent sorting by cows (Kononoff *et al.,* 2003).

How feed is presented to cows also impacts PEF requirements. Consistent access to feed and how it's mixed can affect how much fiber is effective. Feed sorting, where cows select against long particles, can reduce the effective fiber intake despite adequate formulation on paper. Providing well-mixed, palatable feed that discourages sorting is crucial for maintaining the required level of PEF (DeVries *et al.,* 2008). Individual cow genetics and health status can influence how fiber is digested and utilized. Certain breeds or genetic lines might digest fiber more efficiently or require different amounts of PEF for optimal health and productivity. Additionally, the health status of cows, particularly concerning the rumen and liver, can impact fiber digestion capabilities and needs (Krause and Combs, 2003).

Measurement of PEF

Accurate measurement of PEF is essential for formulating diets that ensure optimal ruminal function and animal health. The measurement of PEF primarily focuses on the physical characteristics of the feed, particularly its ability to stimulate chewing and rumination, which are vital for saliva production and rumen buffering. The Penn State Particle Separator (PSPS) is one of the most used tools for assessing PEF. This device segregates feed particles into different-size fractions using a series of sieves with varying mesh sizes. The larger particles, retained on the upper sieves, are considered more effective in promoting rumination and are thus attributed a higher PEF value. The proportion of feed retained on these sieves, typically greater than 1.18 mm or 19 mm, correlates with the physically effective fiber content of the diet.The PSPS developed in 1996 by Penn State University, represents a significant advance in the measurement of feed PS for dairy cattle diets(Lammers *et al.,* 1996). This cost-effective tool has become routine in evaluating the physical characteristics of forages and total mixed rations (TMR). Initially consisting of two sieves with openings of 19.0 mm and 8.0 mm, the PSPS was later enhanced with a third sieve of 1.18 mm to provide a more detailed assessment, aligning with the S424 standard of the American Society of Agricultural Engineers (ASAE). PEF is thought to be more effective in forecasting rumen conditions because it includes data on the chemical NDF concentration and fractions of diet-related particles (Zebeli *et al.,* 2006).

PSPS is now often used as an efficient and useful way to assess the size of feeds and TMR on farms regularly (Lammers *et al.,* 1996). The existing feed tables have made it impossible to assess the physical efficacy of the diet and the amount of fiber that dairy cows require. This is primarily because they do not consider the physical features of the feedstuff, such as particle size (NRC, 2001). To include PS in dietary information the concept of PEF is important because it combines data on structural characteristics (PS) and chemical contents (NDF), which work together and in concert to maintain acid-base balance and ruminal fermentation (Allen, 1997). Thus, using peNDF in diet design offers a viable approach to assess dairy cows' adequate intake of dietary fiber. Feedstuff peNDF content is determined by multiplying its NDF concentration by the physically effective factor. The computation is predicated on the idea that a standard feed that is hypothetically created would function best if it had 100% NDF and 100% peNDF. PEF ranges from 0 (meaning NDF is not physically effective) to 1 (meaning NDF fully promotes chewing and rumen buffering) (Zebelia et al., 2010). Therefore, the physical shape of the meal and the NDF content determine the estimation of peNDF. Normal rumen conditions are influenced by the fermentability properties of the feed in addition to the ideal quantity of peNDF (Banakar *et al.,*2018).

Another traditional method includes evaluating the length of forage fibers manually or using image analysis. Longer forage particles are generally associated with increased PEF as they require more chewing time, produce more saliva, and contribute to better rumen function.
One challenge in measuring PEF is the dynamic nature of fiber effectiveness in the rumen, which can be influenced by factors like feed processing, animal feeding behavior, and individual animal differences in rumination. Therefore, static measurements like those obtained from the PSPS might not fully capture the functional effectiveness of fiber in stimulating rumination and saliva production. Moreover, the physical form of non-forage fiber sources and the effects of feed processing (e.g., grinding, pelleting) can alter the physical effectiveness of the fiber. Therefore, quantifying fiber based on particle size or length may not adequately reflect its true effectiveness in the rumen.

Effects of PEF on Rumen Function in Dairy Cows

Maintaining a stable rumen pH is vital for the health and efficiency of rumen microbial populations. A stable pH prevents conditions such as subacute ruminal acidosis, which can occur when highly fermentable feeds quickly lower the pH. Adequate levels of peNDF encourage consistent rumination activity, which is directly linked to saliva production. Saliva contains bicarbonate and phosphate buffers that help stabilize rumen pH. Research by Plaizier *et al.,* (2017) highlighted that incorporating sufficient peNDF could effectively mitigate the fluctuations in rumen pH associated with high-grain diets.

VFAs are crucial metabolic energy sources for dairy cows, and their production is significantly influenced by peNDF. The fermentation of fiber, primarily influenced by the adequacy of peNDF, leads to the production of acetate, propionate, and butyrate. Beauchemin (2018) noted that appropriate peNDF levels promote a balanced VFA profile, which supports optimal energy utilization and can impact milk composition, particularly by enhancing milk fat content. The diversity and functionality of rumen microbes are enhanced by the presence of peNDF. Effective fiber provides a substrate that supports fibrinolytic bacteria, essential for the breakdown of fiber. According to Mertens (2009), diets formulated with optimal levels of peNDF support a healthier balance of rumen bacteria, enhancing fiber digestion and overall nutrient absorption.

Effective rumen motility is crucial for the mixing of rumen contents, which ensures that all ingested material is adequately exposed to microbial action. Zebeli *et al.,* (2012) demonstrated that optimal peNDF levels enhance the physical movements of the rumen, facilitating better mixing and reducing the likelihood of layering within the rumen content. This uniform mixing is essential for the optimal performance of microbial populations and for maximizing digestion and absorption of nutrients. Cud chewing is an essential activity in dairy cows that mechanically reduces food particle size, making nutrients more accessible for microbial action. Additionally, the act of cud chewing is a natural process that significantly contributes to saliva production. Allen (2000) elaborated that increased chewing time, stimulated by adequate peNDF, leads to greater saliva production, which is beneficial for buffering the rumen and preventing acid buildup.

Impact of PEF on Dairy Cow Performance: Milk Yield, Milk Composition, and Feed EfficiencyGrant and Albright (2001): Effects of Grouping on Intake and Behavior

Grant and Albright (2001) explored how different social and environmental conditions, including diet structure, affect the feeding behavior and intake of dairy cattle. Their study notably addressed how variations in peNDF could impact these factors, ultimately influencing milk yield. The research involved grouping dairy cows under different feeding regimes, with varying levels of peNDF. The study monitored intake levels, rumination behavior, social interactions, and milk yield across different groups. The study found that higher levels of peNDF in diets led to increased rumination times and more stable intake patterns. These conditions resulted in improved milk yields. Cows in environments with adequate peNDF exhibited less competitive behavior at feeding times, which contributed to more consistent feed intake and nutrient absorption.

Beauchemin and Yang (2005): Influence of peNDF on Milk Fat Synthesis

Beauchemin and Yang (2005) conducted a detailed study to examine the impact of peNDF on milk composition, particularly focusing on milk fat percentage. This study is critical as it links dietary fiber with biochemical processes in milk synthesis. Dairy cows were fed diets with controlled peNDF levels, and measurements of milk composition, including fat and protein percentages, were taken. The study also analyzed rumen fermentation patterns and their relation to dietary inputs. Increased peNDF levels were associated with a higher milk fat percentage. The study attributed this to enhanced acetate and butyrate production during fermentation, which are known precursors for milk fat. However, excessive peNDF led to decreased overall feed intake, mildly affecting protein yields in milk.

Zebeli *et al.,* (2012): Rumen Fermentation Efficiency and Feed Efficiency

Zebeli *et al.,* (2012) focused on how peNDF affects rumen fermentation efficiency and, consequently, overall feed efficiency in high-producing dairy cattle. Their research provides insights into the metabolic and physiological implications of fiber in dairy diets. The study evaluated dairy cows fed with varying levels of peNDF, examining detailed ruminal pH levels, VFA production, and feed efficiency metrics. The research used advanced ruminal cannulation techniques to gather precise data. Optimal levels of peNDFimproved ruminal fermentation efficiency, evidenced by more stable pH levels, and increased total VFA production. This resulted in better nutrient digestibility and utilization, enhancing milk production per unit of feed consumed.

Oba and Allen (1999): Effect of peNDF on Dry Matter Intake and Milk Production

Oba and Allen (1999) investigated the relationship between peNDF levels and dry matter intake, milk production, and feeding behavior in dairy cows. The study employed a controlled experimental design where multiple groups of dairy cows were fed diets with systematically varied peNDF levels to assess impacts on intake and milk production efficiency. The study found that increased peNDF levels were associated with higher dry matter intake and improved milk yield. The researchers highlighted that peNDF enhances rumen fill, which can stimulate appetite and improve feed intake consistency over time.

Stone (2004): Influences of peNDF on Milk Components and Rumen Health

Stone (2004) focused on the effects of peNDF on milk components, specifically protein and lactose, and overall rumen health. Dairy cows were fed varying levels of peNDF, and changes in milk composition and signs of ruminal acidosis were monitored. Stone reported that appropriate levels of peNDF not only improved milk fat but also had a positive effect on protein and lactose concentrations. Additionally, cows showed fewer signs of ruminal acidosis, indicating better rumen health.

Krause and Combs (2003): Dietary Fiber and Somatic Cell Count

Krause and Combs (2003) explored the relationship between dietary fiber, specifically peNDF, and somatic cell count, an indicator of mastitis in dairy cows. The research tracked somatic cell counts in cows fed diets with different peNDF levels to determine if there was a correlation between fiber intake and udder health. Their findings indicated that higher peNDF levels are associated with lower somatic cell counts, suggesting better immune health and lower incidence of mastitis.

Harvatine and Allen (2006): PEF and Diurnal Patterns of Feed Intake

Harvatine and Allen (2006) examined how varying levels of peNDF affect the diurnal patterns of feed intake and rumination in dairy cows. The study analyzed feed intake frequency and duration across different times of the day in cows consuming diets with different peNDF levels. Results showed that cows with higher peNDF in their diets had more consistent feed intake patterns throughout the day and engaged in longer periods of rumination.

PEF and Its Role in Preventing Metabolic Disorders

Subacute ruminal acidosis (SARA) is a common metabolic disorder in dairy cows, primarily caused by insufficient fiber intake, which leads to lower rumen pH levels. Plaizier *et al.,* (2017) have identified peNDF as a crucial dietary component in preventing SARA. The presence of adequate peNDF promotes effective rumination and saliva production, which are natural buffers that help maintain a stable rumen pH. The researchers found that diets optimized with sufficient peNDF reduce the incidence of SARA by ensuring better fermentation processes and preventing the rapid accumulation of lactic acid.

A lack of adequate fiber can lead to decreased rumen motility, increasing the risk of displaced abomasum, another significant health issue in dairy cows. Stone (2004) highlighted that appropriate levels of peNDF enhance rumen motility and stabilize the physical fill of the rumen, which can prevent the abomasum from becoming displaced. Diets with adequate peNDF are associated with lower incidences of this condition by supporting normal digestive movements and preventing the abnormal settling of heavier feed components.

PEF and Its Effects on Digestive Disturbances

Digestive disturbances such as impaction and constipation can occur when there is insufficient effective fiber in the diet. Oba and Allen (1999) demonstrated that peNDF not only impacts the amount of intake but also the physical characteristics of the digesta. Their findings suggest that sufficient peNDF in the diet ensures regular bowel movements and prevents the dry, compacted feces associated with these conditions, thereby maintaining regular digestive tract health.The balance of microbial populations in the rumen is vital for overall digestive health. Krause and Combs (2003) found that diets with appropriate levels of peNDF support a diverse and robust microbial ecosystem in the rumen. This diversity is crucial for the efficient breakdown of nutrients and prevents the overgrowth of harmful bacteria that can lead to infections and inflammations of the rumen lining. By supporting a healthy microbial balance, peNDF plays a critical role in promoting overall digestive health.

Recommendations for Formulating Diets with Adequate peNDF

Different production stages and goals (e.g., high milk yield vs. pregnancy maintenance) require specific peNDF levels. For high-producing dairy cows, Beauchemin and Yang (2005) recommend diets with higher peNDF levels to support intense metabolic demands and maintain milk fat content. During late lactation or dry periods, slightly lower levels of peNDF may be sufficient, as the energy demands are not as high. Diets must also be tailored to available feed ingredients and economic constraints. For instance, areas with access to high-quality forages can rely more on natural fiber sources, whereas regions needing to import feeds might use processed fiber supplements to meet peNDF requirements. Allen (2000) notes the importance of balancing cost and feed availability with nutritional needs to optimize dairy cow health and productivity.

The particle size of forages plays a critical role in their effectiveness as peNDF. Larger particles promote more chewing activity and saliva production, which are beneficial for rumen buffering. Ensuring that a significant proportion of the diet remains above the critical size to stimulate rumination is key. In situations where natural forage quality or quantity is insufficient, supplemental fiber sources can be used to meet peNDF requirements. Options such as beet pulp, soy hulls, or cottonseed hulls are effective at increasing peNDF without excessively diluting nutrient density. Oba and Allen (1999) highlight the use of these supplemental fibers to enhance peNDF in diets predominantly based on finely ground concentrates or poor-quality forages. Regular monitoring of cow health, production parameters, and rumen pH is essential for timely adjustments to the diet. This adaptive management approach helps in responding to changes in feed quality, cow productivity, or health status, ensuring that peNDF levels are continually optimized. Krause and Combs (2003) emphasize the importance of ongoing assessment to maintain effective fiber levels, particularly in herds experiencing fluctuations in milk fat percentage or signs of ruminal acidosis.

Economic and Environmental Implications of Formulating Diets to Meet PEF Targets in Dairy Cows

Feed is the largest variable expense in dairy production, and the inclusion of adequate peNDF can influence feed costs directly. High-quality forages that are rich in effective fiber tend to be more expensive, and depending on geographical and seasonal availability, the costs can fluctuate significantly (Allen, 2000). Incorporating alternative fiber sources like beet pulp, soy hulls, or cottonseed hulls, as suggested by Oba and Allen (1999), might mitigate some of these costs but can also introduce variability in the diet that may affect rumen health and milk production. Diets formulated with adequate levels of peNDF are linked to improved cow health, enhanced milk yield, and better milk components, particularly fat content (Beauchemin and Yang, 2005). Improved health reduces veterinary costs and culling rates, enhancing the longevity and productivity of the herd. Moreover, optimal peNDF levels can improve feed efficiency, reducing the overall amount of feed needed per unit of milk produced, which can significantly impact profitability (Zebeli *et al.,* 2012). The prevention of disorders such as subacute ruminal acidosis

(SARA) and displaced abomasum, through diets rich in peNDF, not only saves costs associated with treatments and potential losses of affected animals but also boosts overall production efficiency (Plaizier *et al.,* 2017). These health benefits translate into economic advantages by stabilizing milk production and improving the quality of milk, which can command higher prices depending on market conditions.

Formulating diets to optimize peNDF not only affects economic outcomes but also impacts environmental sustainability. Efficient use of fiber-rich forages can improve nutrient utilization by cows, reducing the excretion of undigested nutrients and lowering the environmental load of waste products (Krause and Combs, 2003). Additionally, improving feed efficiency through adequate peNDF reduces the per-unit environmental impact of milk production by decreasing the greenhouse gas emissions per liter of milk produced. Diet formulations that efficiently use locally available for ages can reduce the need for transported feed ingredients, thereby decreasing the carbon footprint associated with dairy production. However, the cultivation of high-quality forages with adequate peNDF levels requires careful management to avoid the overuse of land resources and to ensure that soil health is maintained (Stone, 2004). Sustainable farming practices that include crop rotations with fiber-rich forages can enhance biodiversity and improve ecosystem health. These practices help maintain soil structure and fertility, and by reducing chemical inputs, they can mitigate the adverse effects of intensive farming practices on local flora and fauna (Harvatine and Allen, 2006).

CONCLUSION

In summary, PEF plays a critical role in dairy cow nutrition and rumen physiology, influencing various aspects of rumen function, animal health, and productivity. Achieving the right balance of PEF in dairy diets is essential for maintaining rumen health, optimizing nutrient utilization, and preventing metabolic disorders such as subacute ruminal acidosis (SARA). This review underscores the importance of considering factors such as diet composition, feeding practices, and cow physiology when formulating diets to meet PEF targets. Additionally, the review highlights the economic and environmental implications of optimizing PEF levels in dairy diets, emphasizing the potential benefits for both farm profitability and environmental sustainability. Overall, understanding the role of PEF in dairy cow nutrition is essential for maximizing animal performance and promoting sustainable dairy production systems.

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