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Effects of physically effective fiber on rumen and milk parameters in dairy cows: A review

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ABSTRACT

The objective of this paper is to review the effects of physically effective fiber on rumen function, milk yield, and milk composition and the optimum requirement for dairy cows. Dietary fiber is a vital component of feed that regulates the rumen functions and improves milk quality and milk yield in ruminants. The appropriate particle size and quantity of dietary fiber in the diets of dairy cows help to prevent the occurrence of ruminal disorders and promote healthy rumen functioning and productivity. Currently, sub-acute ruminal acidosis is a common problem in a modern dairy production system. The disease is caused by lack of adequate amount of physically effective dietary fiber in animal feed. Long sized dietary fiber particles stimulate chewing and saliva production would help to maintain reticulo-ruminal buffering capacity. The optimum requirement of fiber for dairy cows depends on the physical form of the fiber source, the chemical composition of the total ration, the stage of lactation and level of production.

Key words: Milk composition, Physically effective fiber, Requirement, Rumen fermentation.

Efficient utilization of diets by dairy cows is influenced by the chemical composition and physical characteristics of the ration (Mertens, 1997). The current feeding systems of dairy cattle recommend concentrate rich diets to meet the high nutritional needs of cows during lactation and hence maximizing cost-efficiency in the production (Humer *et al*., 2018). However, such diets can cause ruminal fermentation disorders (Zebeli *et al*., 2011; Enemark, 2009) by reducing the pH in the rumen and increasing the incidence of sub-acute ruminal acidosis (Mertens, 2000; Morgante *et al*., 2007). Sub-acute ruminal acidosis is a common metabolic disorder in a modern dairy production system and it affects rumen health and reduces productivity. The disease is caused by insufficient amount of fiber in the daily diets (Zebeli *et al*., 2008; Krause and Oetzel, 2006). The physical effectiveness of fiber is mainly measured based on the ability of the physical characteristics of fiber to stimulate chewing and buffer secretion (Mertens, 1997). Therefore, the concept of physically effective fiber is important and can be expressed as the extent to which the physical structure of fiber stimulates chewing and salivary secretion needed to buffer and contributes to contribute to the floating mat of large particles in the rumen (Mertens, 1997; White *et al*., 2017).

Finding an optimal balance between physically effective fiber and readily degradable carbohydrates in the diet is critical not only for maintaining proper rumen activities (Zebeli *et al*., 2006; Plaizier *et al*., 2008; Kröger *et al*., 2019); but also for a stable metabolic health status and enhancing the productivity of the dairy production sector (Ametaj *et al*., 2010; Zebeli *et al*., 2011).

Increased intake of physically effective fiber increases chewing activity, salivary buffer supply, rumen motility and mixing, ruminal pH and maintains proper rumen functioning (Yang and Beauchemin, 2006; Zebeli *et al*., 2012). Furthermore, it improves total digestibility (Yansari *et al*., 2004; Yang and Beauchemin, 2005) and increases milk fat content (Yang *et al*., 2001; Kononoff and Heinrichs, 2003a). The optimum amount of physically effective fiber for dairy cows depends on the actual particle size, the amount of potentially degradable fiber, rate of digestion and passage as well as the type of the diet (Allen, 1997; White *et al*., 2017).

Therefore, the objective of this paper is to review the effects of physically effective fiber on rumen functions, milk yield and milk composition and the optimum requirement for dairy cows.

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Feed particle size and sorting

Penn State Particle Separator (PSPS) box is a common tool used for evaluating the particle size of forages and total mixed rations (TMR) (Linn, 2005; Esmaeili *et al*., 2016). The particle size of feeds can be changed by different mechanical activities including sorting, mixing, chopping, storing, harvesting etc. It has been designed in four different sized screen boxes (≥19, ≥8, ≥1.18 and <1.18 mm). The top screen retains particle sizes of greater than 0.75 inch which are considered as the physically effective fiber that stimulate chewing, rumination and floating mat formation for buffering.

When the particle size of the corn silage is greater than 0.75 inch in the TMR, sorting becomes a problem and when the corn silage particle size is smaller than 0.33 inch, the milk production declines because the finely chopped corn silage does not support the rumen health (Heinrichs, 2013; Robin *et al*., 2017). The recommended particle size for different feedstuffs is summarized in Table 1.

Feed sorting is a common practice in dairy cattle feeding system which affects the intake of essential nutrients from the TMR. It is an ongoing concern for dairy producers due to its effect on the nutrient composition of the ration consumed and consequent on normal rumen metabolism (DeVries *et al*., 2008), as well as milk productivity and composition (Sova *et al*., 2013). Too much sorting in a TMR can result in over consumption of rapidly fermentable carbohydrates and increase the risk of sub-acute ruminal acidosis (DeVries *et al*., 2008).

Feed containing long particle size increases intake of high fermentable carbohydrates and decreases intake of effective fiber which results in low rumen pH and alteration of milk composition (Miller-Cushon and DeVries, 2017; Leonardi *et al*., 2005a). The rate of forage inclusion, level of feeding, particle size and dry matter content are the main factors that determine feed sorting process. Feeding strategies that increase time to manipulate rumen metabolism while decrease feeding frequency and increases feed intake level may result in feed sorting process (Miller-Cushon and DeVries, 2017).

EFFECTS OF PHYSICALLY EFFECTIVE FIBER

Rumen functions and milk composition

Excessive inclusion of fiber in the diet causes decrease in the DM intake, energy density and milk productivity. On the other hand, insufficient amount of fiber in the diet disrupts rumen function and causes decline in milk productivity (Mertens, 1997). Therefore, dairy cows should be fed diets with adequate fiber content and appropriate particle size for proper physiological function and maximum productivity. Zebeli *et al*. (2012) reported that feed containing particle with a size greater than 1.18 mm can stimulate rumination, but particle with size greater than 8 mm can form rumen mat. Metabolic disorders in dairy cow occur when minimum level of fiber required are not met (consuming finely chopped forages), this results in decrease digestibility of total dry matter, milk fat percentage, displaced abomasum and

Table 1: Particle sizes of some feeds and their optimum percentage for dairy cows measured by Penn State Particle Separator.

Screen	Pore size (inch)	Particle size (inch)	Corn silage (%)	Haylage (%)	TMR (%)
Upper sieve	0.75	> 0.75	3-8	10-20	2-8
Middle sieve	0.31	0.31-0.75	45-65	45-75	30-50
Lower sieve	0.16	0.16-0.31	20-30	30-40	10-20
Bottom pan	NI	<0.16	<10	<10	30-40

Where: NI- not identified; TMR- total mixed ration (Adapted from Linn, 2005; Heinrichs, 2013; Miller-Cushon and DeVries, 2017).

Table 2: Effects of different dietary fiber particle sizes on ruminal pH, chewing rate and milk composition.

Sources	Particle size (mm)	Chewing rate	Ruminal pH	Saliva production	Milk composition	References
Alfalfa silage	14.3	Increased	5.9-6.3	Increased	MP decreased; MF content increased	Thomson *et al.* (2017)
	>4		No effect		MP increased and MF decreased	
TMR	>19	Higher	NA	Higher	Higher MYHigher in	Esmaeili *et al.* (2016)
	<19 & ≥8	Higher	NA		MF (higher F:P)	
	<8 & ≥1.18	Lower	NA	Lower	Lower in MF	
	28.6	higher	6.08	Higher	32.1 kg/d MY (3.3% MF)	Yang and Beauchmin (2006)
	15.9	Higher	6.08	Higher	32.4 kg/d (3.23 MF)	
	4.8	lower	5.99	Lower	31.5 kg/d (3.24 MF)	
	Chopped hay (10 mm)	higher	5.97	198.9 $mlmin^{-1}$	29.4 kg/d (3.92 MF)	Beauchmin *et al.* (2003)
	Ground hay (4 mm)	Lower	5.78	191.1 $mlmin^{-1}$	29.2 kg/d (3.78 MF)	

Where: TMR- total mixed ration; MP- milk protein; MY: milk yield; MF- milk fat; NA- the data is not available.

increase incidence of rumen parakeratosis, laminitis, acidosis and low fat cow syndrome (Dijkstra *et al*., 2012; Heinrichs, 2013). Diets with extra coarse particles induce sorting, fill the rumen and reduce dry matter intake (DMI) and milk production (Heinrichs and Kononoff, 2002; Nasrollahi and Khorvash, 2014).

Heinrich (2013) reported that diet containing particle of smaller size reduced the time cows spent on chewing feed and decreased rumen pH. The volume of saliva decreases when cows spend less time on chewing feed and this results in low buffering of the rumen environment. As the particle size of physically effective fiber increased; the acetate content in the rumen also increased, whereas the propionate content decreased (Thomson *et al.,* 2017; Wang *et al*., 2017; Liu *et al*., 2018). The linearly increased in acetate production was consistent with the linearly increased in digestibility of neutral detergent fiber (NDF) and acid detergent fiber (ADF) and this is further confirmed by the growth of ruminal cellulolytic bacteria which was promoted by physically effective fiber (Liu *et al*., 2018). As cellulose and hemi-cellulose content in the diet increases, the acetate and butyrate concentration in the rumen and blood also increases; consequent the milk fat content increases (Linn, 2005). Esmaeili *et al*. (2016) reported that the particle size of TMR can significantly influence the fat content of milk and fat to protein ratio and lactose and solids contents also tended to increase. The general flow of major nutrients from the diet via rumen to blood and udder is illustrated in Fig 1.

Increase in the particle size of ryegrass increases chewing activity and stabilized ruminal pH, but reduces DMI, ruminal volatile fatty acid production and diet digestibility (Cao *et al*., 2013). Different feed ingredients are responsible for the production of different products in the rumen. The effects of different physically effective fiber sources on rumen function and milk composition are shown in Table 2.

Rumen microbiota

The gastrointestinal tract is a complex ecosystem which is rich in microbes such as bacteria, protozoa, fungi and differs in numbers and proportion. The bacteria comprise more than 60% of the total population of microbes in the rumen (Bickhart and Weimer, 2018). Bacteria are mainly

Table 3: Different types of diet compositions and their effect on rumen microbes.

Feed types	Rumen microbes	Trend	References
70% roughage and 30% concentrates diet	Protozoa	Decreased	Dennis *et al.* (1983)
	Cellulolytic bacteria species	Increased	Erfle *et al.* (1979)
70% concentrates and 30%	Protozoa	Increased	Dennis *et al.* (1983)
roughage diet	Starch digesting bacteria (*Streptococcus boris, Bacteroides ruminicola*)	Increased	Erfle *et al.* (1979)
65% concentrate for 1 week	*-Fibrobacter-Shuttleworthia*	Decreased by 70%	Neubauer *et al.* (2018)
		Increased by 98%	
100% roughage for 1 week	*Fibrobacter*	Increased by 70%	
42.1% peNDF $_{\geq 8mm}$	*Fibrobacter succinogenes* and *Ruminococcus flavefaciens*	Decreased	Li *et al.* (2014)
14.5% peNDF $_{\geq 8mm}$	*Fibrobacter succinogenes* and *Ruminococcus flavefaciens*	Increased	

Table 4: The physically effective fiber requirement for dairy cows in different types of diets (DM basis).

Description	Requirement (%)	Particle size (mm)	Rumen pH	References
TMR	19	> 1.18	6.0	Zebeli *et al.* (2006; 2011)
	22.3	8	6	Mertens (1997)
	31.2	> 1.18	>6	Kononoff and Heinrichs (2003a)
	18.5	>8	Optimum	NRC (2001)
	10	≥ 19.05	6	NRC (2001)
	10	8-9	Optimum	Yang and Beauchemin (2006)
Corn silage	5-10	≥ 19.05 (0.75 inch)		Kononoff and Heinrichs (2003a)
	3-8	≥ 19.05		Linn, 2005
Haylage	10-25%	≥ 19.05		Kononoff and Heinrichs (2003a)
Sub-acute ruminal acidosis incidence			Below 5.5	elow 5.5 Li *et al.* (2013)
			5.2-5.6	Owens *et al.* (1998)
			5.0-5.2	Zebeli *et al.* (2006)
			<5 (clinical)	John, 2005
			5-5.5 (subclinical)	

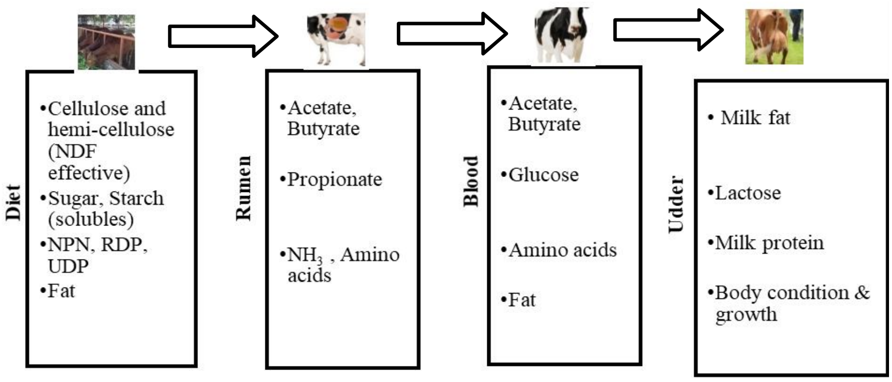
Where: TMR- total mixed ration.

responsible for activities taking place in the rumen though different types of microbes have different roles (Zeineldin, 2018). The nutrition, chemical composition and particle size of diet affect the multiplication and normal functioning of microbes in the rumen. Increasing the amount of fibrous feeds in the diets of ruminants could increase the chewing and ruminating time, saliva production, and reduce the total amount of acids produced in the rumen. This creates favorable condition for proliferation of anaerobic microbes and for efficient ruminal fermentation activities. The specific types and species of microbes produced in the rumen depend on the availability and proportion of fibrous and concentrate feeds as shown in Table 3.

Fermentation acids production

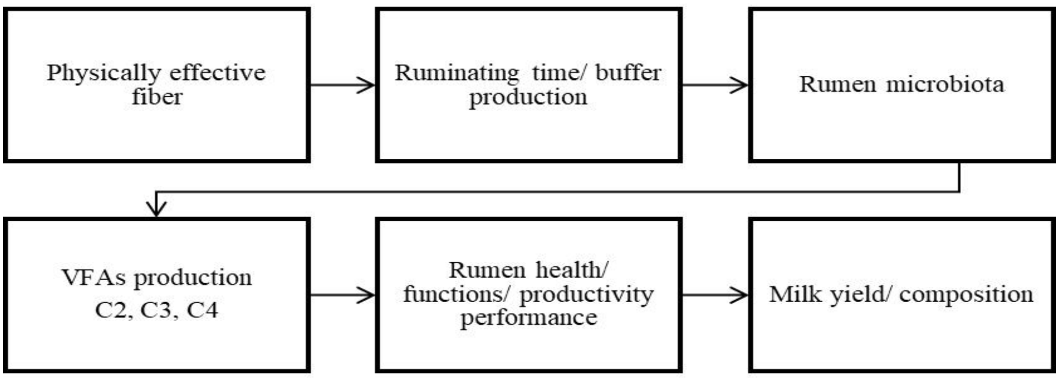
Short-chain volatile fatty acids (SCVFAs) are produced in the rumen and are responsible for reducing in rumen pH (Chang *et al*., 2010; Li *et al*., 2013). For optimum ruminal microbial growth and nutrient degradation, the pH should range from 6.25 to 6.60 and can only be attained by addition of physically effective fiber. Dairy cows that feed rapidly fermentable grains often have low rumen pH due to the excess amount of acid produced in the rumen and low dry matter intake (Allen, 2000). The rate of acids production by fermentation of organic matter (OM) in the rumen (74,000 meq/d) is nearly twice the rate of salivary buffer secretion (41,000 meq/d) (Allen, 1997). This implies that adequate amount of physically effective fiber is important to facilitate buffering.

The acids produced in the rumen during fermentation would be removed by absorption, neutralization and passing from the rumen to body through the omasal orifice (Allen, 1997; Dijkstra *et al*., 2012). Hydrogen ions produced in the rumen are rapidly removed by absorption during buffering process to maintain physiological pH. Buffering is the most important mechanism for the removal of hydrogen ions from the solution (Allen, 1997). A cow can produce 150L of saliva daily (John, 2005) that contains bicarbonate and hydrogen phosphate ions; which are responsible for removal of hydrogen ions from the ruminal solution by a combination of alkalization and buffering (Allen, 1997). Generally, the major role of physically effective fiber for dairy cows is illustrated in Fig 2.



Where: NDF- neutral detergent fiber; NPN- non-protein nitrogen; RDP- rumen degradable protein; UDP-Undegradable dietary protein. Acetate and butyrate are mainly produced from cellulose and hemicellulose sources of diets, and the milk fat content will be higher. When the diet is higher in sugar and starch content, the main products in the rumen and blood are propionate and glucose respectively, and the milk will be higher in lactose content. Nutrients from the diet contribute for body condition and growth of the cow.

Fig 1: Pictorial illustration of the flow of major nutrients from different diet components via rumen to blood and udder (Adapted from Linn, 2005).



Where: VFAs- volatile fatty acids, C2- Acetate, C3- Propionate, C4- Butyrate

Fig 2: The process and roles of physically effective fiber on dairy cow rumen functions, milk composition and yield.

Physically effective fiber requirement for dairy cows

Fiber requirements for dairy cattle depend on both the physical effectiveness and the quantity of acids produced during fermentation (Allen, 1997). The amount of physically effective fiber in a diet is based on the forage particle size / chops length, concentrate-to-forage ratio, types of forages and dietary NDF content (Mertens, 1997).

Linn (2005) reported that the particle size of the diets should be >0.75 inches and comprised approximately 8% of the total feed. The other 30% of the feed falls in a particle size between 0.31 and 0.75 inches and the remaining 62% of the feed are < 0.31 inches. The physically effective fiber requirements for high-yielding dairy cows were estimated to be 19% of the ration on dry matter (DM) basis (4.1 kg/d or 0.6 kg/100 kg of body weight) which would maintain a ruminal pH at normal level (Zebeli *et al*., 2006). Recently, Kröger *et al*. (2019) reported that the amount of physically effective fiber in the daily ration depends on the percentage of the starchy feeds in the diet. Different studies on the requirement of physically effective fiber for dairy cows are summarized in Table 4.

Sub-acute ruminal acidosis

sub-acute ruminal acidosis is a common metabolic disorder in intensive (well-managed and high yielding) ruminant dairy production system (Li *et al*., 2014). The disease is mainly caused by lack of physically effective fiber and it affects rumen function, animal health and productivity (Zebeli *et al*., 2008; Kröger *et al*., 2019). Accumulation of lactic acid in the rumen is the main characteristics of ruminal acidosis (Luo *et al*., 2017). Currently, nearly 20% of the cows kept under intensive production system are affected by this disease regardless of the stage of lactation, production level and management system (Kleen, 2012). Production of high concentrations of volatile fatty acids (VFAs) especially propionic and butyric acids in the rumen might cause sub-acute ruminal acidosis. The ratio of acetate to propionate significantly decreases as the non-fiber diets increases; this increases the incidence of the disease (Sun *et al*., 2018). Accumulation of VFAs due to high proportions of fermentable concentrate and low physically effective fiber can result in low pH (Yang and Beauchemin, 2006; Liu *et al*., 2018).

Causes and symptoms

Excessive intake of rapidly fermentable carbohydrates, inadequate ruminal adaptation to a highly fermentable diet and inadequate ruminal buffering are the major causes of ruminal acidosis (Krause and Oetzel, 2006; Chaidate *et al*., 2014; Zebeli *et al*., 2008). Sun *et al*. (2018) reported that as the level of non-fiber carbohydrates to neutral detergent fiber (NFC/NDF) ratio increases from 1.4 to 3.23% the concentrations of propionate and butyrate VFAs also increased, the ratio of acetate to propionate decreased as well as pH dropped significantly in dairy goats. Decreasing in ruminal pH does not necessarily indicate incidence of sub-acute ruminal acidosis however, it is important to consider how many consecutive hours per day the pH dropped from the threshold (5.5) (Nocek, 1997; Krause and Oetzel, 2006; Li *et al*., 2013). The only method to detect the incidence of sub-acute ruminal acidosis is through continuous measurement of the ruminal pH using fistulated animal. The physical appearance of feces and feeding pattern (Enemark, 2009), milk variables, blood minerals and metabolites, liver enzymes and chewing activities could also be used to detect the incidence of sub-acute ruminal acidosis (Kröger *et al*., 2019).

Treatments

Changing diet is the most efficient method to prevent sub-acute ruminal acidosis in dairy cattle (Rojo-Gimeno, 2018; Kröger *et al.,* 2019). Regulating and stabilizing the ruminal pH and concentrations of VFAs at a recommended level by increasing the amount of physically effective fiber that will stimulate chewing and saliva production can minimize the incidence of the disease. Moreover, reducing the amount of highly fermentable concentrate feeds and application of antibiotic treatments and buffers are the other options to treat sub-acute ruminal acidosis. In United States and Europe, application of buffers such as sodium or potassium bicarbonate, sodium sesquicarbonate, sodium bentonite, calcium carbonate in treatment of sub-acute ruminal acidosis is widely practiced in dairy farms (Enemark, 2009).

CONCLUSION AND RECOMMENDATION

Concentrate rich diets are still recommended for high yielding dairy cows, but, must contain sufficient amount of physically effective fiber that stimulates rumination, saliva production and rumen buffering to maintain and facilitate better rumen activities, and prevent sub-acute ruminal acidosis. Extremely coarse and fine particle sizes in diet are the two major causes of low dry matter intake and sub-acute ruminal acidosis in dairy cows respectively. During formulating diets to meet nutrient requirements of dairy cows, physical effectiveness of the fiber, the stage of lactation, the amount of rapidly fermentable starch and production level of fermentation acids should be taken into account. Future studies should focus on the physical characteristics of diets, the effectiveness of diet fibers, their degradability potential and passage kinetics, and nutritional contribution to animal physiological performance and productivity. Moreover, the role of indigestible NDF or potentially digestible NDF in normal function of rumen and animal health should be evaluated.

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