Dietary Fiber Requirements and Influencing Factors in Young Ruminants: Postprint

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Abstract

The source and composition of fibrous carbohydrates (FC) in diets for young ruminants play an important role in regulating their growth, development, and establishment of rumen function. Varying in source and particle size, they exert differential effects on physiological parameters such as feed intake and digestion, rumen fluid pH, and rumen development in growing young ruminants. This article reviews recent research on the source and particle size of neutral detergent fiber (NDF) in diets for young ruminants, summarizes their effects on young ruminants from three aspects: production performance, rumen fermentation, and rumen development, and discusses the related mechanisms.

Full Text

Preamble

Research Advances in Fiber Nutrition Requirements and Influence Factors for Young Ruminants

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Abstract: The source and composition of fibrous carbohydrates (FC) in diets for young ruminants play a crucial role in regulating their growth, development, and establishment of rumen function. However, both the source and particle size of dietary FC exert differential effects on feed intake and digestion, rumen fluid pH, and rumen development in growing young ruminants. This article reviews recent research on neutral detergent fiber (NDF) source and particle

size in starter feeds for young ruminants, summarizing their effects on performance, rumen fermentation, and rumen development from three perspectives, and discusses the underlying mechanisms.

Keywords: young ruminants; neutral detergent fiber; fiber source; particle size; rumen development

For young ruminants, the nutritional level of pre-weaning starter feed is a critical factor regulating rumen microbial colonization and epithelial functional development. The fermentation products of non-fibrous carbohydrates (NFC) in starter feed—volatile fatty acids (VFA)—provide energy for the animal after absorption through the rumen epithelium, while butyrate promotes rumen epithelial cell renewal and enhances absorptive function [1]. Additionally, the main component of FC in starter feed is neutral detergent fiber (NDF), which includes cellulose, hemicellulose, and lignin from plant cell walls [2] and serves as an indicator of dietary fiber. Traditionally, fiber requirements for pre-weaning ruminants have been considered limited, primarily because the rumen microbial population is not yet fully established for efficient fiber degradation, and the low energy density of fiber restricts concentrate intake, making it difficult to meet energy demands. Recent studies have found that dietary NDF can improve post-weaning feed intake and stimulate rumen development in young ruminants, though its effectiveness is influenced by NDF source, level, and particle size in the diet [3-5]. Controversy remains regarding optimal NDF provision for young ruminants during the pre-weaning period. Therefore, this article compiles recent domestic and international research on NDF in starter feeds for young ruminants, reviewing the effects of NDF source and particle size on performance, rumen fermentation, and rumen development to provide a theoretical basis for research on pre-weaning fiber nutrition in ruminants.

1. Effects of Starter NDF Source on Performance of Young Animals

1.1 Forage-Derived NDF (FNDF)

Most NDF in ruminant diets originates from forages such as hay or straw, yet research findings on the effects of pre-weaning forage supplementation on performance in young ruminants remain controversial. Numerous studies have demonstrated that FNDF can enhance performance. Terré et al. [6] found that calves with ad libitum access to oat hay before weaning exhibited a 23% increase in post-weaning dry matter intake (DMI), a 30% increase in average daily gain (ADG), and a 5.5% increase in body weight at 64 days of age compared to calves without hay supplementation. Similarly, Daneshvar et al. [7] reported that adding 15% alfalfa hay to calf starter increased starter intake by 33%, DMI by 21%, and ADG by 16% during days 3-74, resulting in an 8% increase in body weight at 74 days. The improved DMI and ADG from pre-weaning forage supplementation may be attributed to higher rumen fluid pH in forage-fed calves, which favors fiber-degrading bacteria and enhances fiber digestibility.

However, other studies have reported that pre-weaning forage supplementation reduces performance. Hill et al. [8] showed that adding 2.5% or 5% hay to calf starter decreased starter intake by 7% and 16%, respectively, and reduced ADG by 6% and 17% during days 1-56, with significantly lower feed efficiency (FE). In another study, Hill et al. [9] added 6% or 9% wheat straw to calf starter and found significant reductions in total DMI (TDMI) and ADG during days 3-56 compared to unsupplemented calves; similar reductions in ADG were observed with 10% or 15% alfalfa hay or 6-9% grass hay. The decreased TDMI and ADG from pre-weaning forage supplementation may result from the underdeveloped rumen in young ruminants, which limits forage degradation capacity. Undigested dietary fiber accumulates in the rumen, increasing digesta weight and volume, which stimulates continuous contact receptors on the ruminal wall and reflexively inhibits feeding behavior, thereby hindering growth [10]. Additionally, studies have shown that DM and organic matter (OM) digestibility significantly decrease when calves are supplemented with alfalfa hay [7], as excessive dietary NDF levels can increase digesta passage rate and reduce gastrointestinal retention time, leading to lower OM digestibility [11].

The mechanisms underlying the effects of pre-weaning forage supplementation on feed intake remain unclear but appear strongly related to starter composition and physical form. Young animals consuming finely ground starter that ferments rapidly produce excessive acid, lowering rumen pH and predisposing to rumen acidosis; in such cases, forage intake helps elevate rumen pH and improve buffering capacity. Conversely, starters containing slowly fermenting whole grains pose a lower acidosis risk, reducing the need for forage, and forage intake may occupy rumen volume and decrease feed intake. In the aforementioned studies, Terré et al. [6] used pelleted starter, while Daneshvar et al. [7] used finely ground meal, both of which ferment rapidly in the rumen and increase calves' willingness to consume forage. The gradually optimized rumen environment from forage intake further stimulates starter consumption, thereby increasing DMI. In contrast, Hill et al. [9] used starter containing slowly fermenting corn and oat grains, leading to fiber accumulation in the rumen and reduced DMI when forage was supplemented.

These divergent results may also stem from differences in forage source, quality, particle size, concentrate and milk feeding strategies, and NDF intake. Different forage sources vary in NDF content and chemical composition, affecting intake and digestibility. For example, legume alfalfa hay contains higher pectin and lower hemicellulose than grass oat hay, offering better palatability and greater intake [12]. One study noted that calves supplemented with alfalfa hay had higher NDF intake (14% vs. 4% of TDMI) than those receiving oat hay, resulting in lower starter intake and DMI, and consequently reduced ADG [13]. Furthermore, forage-supplemented calves have higher NDF intake, increasing gut fill and gastrointestinal weight. Since this increased gut weight contributes to body weight gain, many studies have mistakenly interpreted this apparent weight gain as true body weight gain. Several studies have demonstrated that while forage-supplemented calves showed significantly increased body weight, they also exhibited significantly heavier gastrointestinal tracts and significantly lower carcass weights [8,13-15]. Therefore, differences in gut fill effects must be considered when interpreting results across studies. Research suggests that when hay intake is less than 5% of DMI, the gut fill effect can be ignored while still improving ADG and promoting growth [13]. In summary, most studies indicate that pre-weaning forage supplementation can improve performance, but whether forage can serve as a suitable NDF source in starter feeds requires further investigation.

1.2 Non-Forage Fiber Sources (NFFS)

While NDF in calf and lamb starters primarily originates from grain concentrates and wheat bran, NFFS such as soybean hulls, cottonseed hulls, and beet pulp are also used as NDF sources. NFFS contain high levels of cellulose and pectin but low lignin, enabling rapid rumen fermentation and high digestibility [16]. In adult ruminant diets, replacing some grain with NFFS can increase milk yield and fat percentage while alleviating rumen acidosis [17]. In young ruminants, NFFS can replace some forage and increase DMI and ADG in lambs [18]. NFFS can mitigate adverse effects from rapid starter fermentation without causing the gut fill associated with FNDF, significantly improving DMI, ADG, and body weight at 63 days in Holstein calves when incorporated into starter [19]. However, other research found that adding 5% or 10% cottonseed hulls to starter significantly reduced post-weaning starter intake and ADG compared to unsupplemented calves [8], as cottonseed hulls provided lower energy intake, compromising growth.

Both FNDF and NFFS provide dietary fiber through high NDF content, but their NDF composition differs substantially. Compared to FNDF, NFFS contains more readily degradable components and has higher rumen passage rates, promoting greater performance improvements at appropriate supplementation levels. For instance, calves supplemented with beet pulp before weaning showed significantly increased body weight at 80 days and ADG compared to those receiving alfalfa hay [20-21]; beet pulp supplementation also significantly improved DMI and ADG compared to equivalent wheat straw [20]. However, research on NFFS as an NDF source for regulating growth in young ruminants remains limited, and optimal NFFS types and inclusion levels in starter feeds require further scientific investigation.

Effects of starter NDF source on performance of young ruminant during pre- and post-weaning

2. Effects of FNDF on Rumen Fermentation

Due to low lignification, NFFS is more degradable than forage, with only 35% of the effectiveness of FNDF in maintaining rumen pH [33]; thus, FNDF exerts greater influence on rumen fermentation. Using forage rather than concentrate as the primary NDF source in starter produces completely different effects on chewing behavior, rumen pH, and VFA production, and can regulate rumen fermentation by influencing microbial populations [34].

Rumen fluid pH results from the combined effects of dietary fermentation capacity, saliva secretion, VFA production and absorption rates, and digesta emptying rate. Forage intake elevates rumen pH in young ruminants. Studies have shown that supplementation with oat hay, ryegrass, barley straw, grass hay, and alfalfa hay significantly increases calf rumen pH [13,27-28,32]. This occurs because forage stimulates chewing and rumination, promoting secretion of bicarbonate-rich alkaline saliva that enters the rumen with digesta. Additionally, research found that forage-supplemented calves exhibited a 4-fold increase in monocarboxylate transporter-1 (MCT-1) secretion in rumen epithelium [13]; since MCT-1 co-transports hydrogen ions (H+) with monocarboxylates, increased secretion indicates greater H+ removal from the rumen [35], raising pH.

However, forage consumption reduces rumen VFA production in calves because FC ferments more slowly than NFC, producing less VFA. Moreover, high forage intake reduces OM digestibility, shortening fermentation time in the rumen and decreasing VFA yield [7,13,36]. Studies have reported elevated rumen pH accompanied by reduced VFA production in forage-supplemented calves [15], possibly because fibrous diets remove dead cells from the rumen wall, preventing rumen parakeratosis and enhancing epithelial absorptive function.

Diet composition alters rumen pH and affects VFA production ratios, representing the most important factor determining rumen fermentation type. When young ruminants consume FNDF, rumen fermentation shifts to acetate production. Research demonstrates that forage supplementation significantly increases rumen acetate production [6-7,13-14] and the acetate-to-propionate ratio [6,11,15]. This occurs because high rumen pH from forage-based diets favors fiber-degrading bacteria and increases acetate proportion, whereas concentrate-based diets lower pH, favoring starch-degrading bacteria and increasing propionate and butyrate proportions [37]. Forage supplementation maintains rumen pH at stable, higher levels that benefit cellulose digestion and reduce acidosis risk. However, studies indicate that calves consuming starter can maintain rumen pH <5 for 10 h/d without showing acidosis symptoms [38], suggesting greater tolerance to low pH environments in young animals, which warrants further investigation.

3. Effects of FNDF on Rumen Development

Rumen development manifests as increased weight and volume, along with histomorphological changes including epithelial cell growth and differentiation, papillae length, width, and density, and rumen wall and muscle layer development. Studies show that rumen papillae only begin developing and rumen weight, muscle layer, and mucosal thickness significantly increase after young ruminants consume solid feed [39]. Both the chemical effects of NFC fermentation products from concentrate on rumen epithelium and the physical effects of forage on rumen volume and muscle layer are crucial factors stimulating rumen development.

Concentrate contains high NFC levels, and its fermentation product butyrate stimulates insulin secretion, enhancing rumen epithelial cell mitosis and promoting proliferation by inhibiting apoptosis [1]. Pre-weaning concentrate feeding significantly increases rumen papillae length and width in calves [28,30]. However, excessive butyrate production under high-concentrate conditions can cause abnormal papillae proliferation, leading to branching or malformed development [40]. Furthermore, high-concentrate diets cause excessive keratinized cell layers and rumen parakeratosis, covering papillae with viscous ingesta, hair, and cellular debris that coalesce and block nutrient absorption, potentially damaging rumen epithelium [41].

Traditionally, FNDF is considered insufficient to provide the butyrate needed for papillae development and exerts minimal stimulatory effects on rumen epithelium. Studies have reported significantly reduced papillae length and width in alfalfa-supplemented calves [14]. However, FNDF in starter occupies substantial rumen space, promoting rumen expansion and enhancing rhythmic motility and wall contraction that exercises the muscle layer. Research shows that alfalfa-supplemented calves and lambs exhibit significantly increased muscle layer thickness [22-23,32], rumen wall thickness [14], and rumen weight [14,33] compared to unsupplemented animals. Moreover, FNDF has high abrasive value [42] and can physically remove excessive keratinized layers and dead epithelial cells, playing a vital role in maintaining normal rumen epithelial morphology. Studies found that calves fed high-concentrate versus high-forage diets had 15 versus 4 keratinized cell layers [43], while forage-supplemented calves and lambs showed significantly reduced rumen epithelial and keratinized layer thickness [15,22-23] without abnormal papillae development or coalescence [13]. Therefore, nutritionally complete starter feeds should contain appropriate NFC levels to provide sufficient butyrate for rumen epithelial development and enhanced absorptive function, while also incorporating adequate forage to promote muscle layer development and maintain rumen wall integrity.

4.1 Feeding Behavior

The nutritional value of forage for ruminants depends not only on its chemical composition but also substantially on its particle size, which affects feeding behavior in young ruminants. Research indicates that calves consuming alfalfa hay at 3 mm length exhibited longer chewing and rumination times than those consuming 1 mm hay [44], with lower incidence of non-nutritive oral activities such as licking, tongue rolling, and wood shaving consumption [5,44]. Montoro et al. [5] found that calves supplemented with 10% grass hay at 3-4 cm length selectively consumed the NDF component, whereas those receiving 10% hay at 2 mm length selectively consumed crude protein (CP), with lower digestibility of DM, CP, and NDF, suggesting a preference for concentrate to meet nutritional needs [5,45].

Miller-Cushon et al. [45] fed calves the same two hay particle sizes as Montoro et al. [5], then switched all calves to 3-4 cm grass hay for 3 weeks after 8 weeks. Calves initially fed 2 mm hay continued to selectively consume concentrate components. Young ruminants can selectively consume dietary components based on chewing and rumination patterns, rumen function, and nutritional needs before weaning, with sorting behavior showing considerable individual variation and susceptibility to experiential learning that establishes persistent patterns [45].

4.2 Rumen Development and Performance

Consuming long-particle forage enhances rumen buffering capacity and stimulates rumen development in young animals. Nemati et al. [44] found that calves consuming 3 mm hay had higher rumen pH and acetate-to-propionate ratio at 35 and 70 days compared to those consuming 1 mm hay. Other research reported smaller rumen keratinized layer thickness in calves fed 5.04 mm alfalfa hay versus 2.92 mm hay [15], and thicker rumen muscle layers in calves fed 3-4 cm alfalfa hay compared to 2 mm hay [23].

Particle size also affects feed intake and diet digestibility, thereby influencing performance. In Montoro et al.' s study [5], calves fed long hay had significantly higher post-weaning TDMI and DM digestibility than those fed short-particle hay, with a trend toward improved FE, because long-particle forage provides greater physical stimulation for muscle layer development and rumen motility, promoting enhanced performance. However, Norouzian et al. [23] found that while calves supplemented with 15% 3-4 cm alfalfa hay had lower DMI than those receiving 15% 2 mm hay due to reduced passage rate and increased gut fill, ADG did not differ between groups, suggesting that excessively small forage particle size may compromise performance.

Jahani-Moghadam et al. [46] added 10% chopped (4.0 mm) or pelleted alfalfa hay (5.8 mm) to calf starter, and Suarez-Mena et al. [47] supplemented with 5% straw at lengths of 3.04, 7.10, and 12.70 mm, both finding no significant effects of hay particle size on calf performance. Furthermore, interactions exist between FNDF particle size and inclusion level. Nemati et al. [44] conducted a 2×2 factorial study adding 12.5% or 25.0% alfalfa hay at 1 or 3 mm lengths, finding that at 25% inclusion, calves fed 3 mm hay had significantly higher post-weaning ADG than those fed 1 mm hay, but no particle size effect at 12.5% inclusion. Mirzaei et al. [15] reported that with 8% alfalfa hay inclusion, calves fed 5.04 mm hay had 491 g/d higher post-weaning starter intake than those fed 2.92 mm hay, but no difference was observed at 16% inclusion. Thus, when providing FNDF in starter feeds, particle size effects must be considered when determining inclusion levels, with longer-cut forage allowing for reduced supplementation rates [48]. Current research on pre-weaning forage particle size in young ruminants remains limited, and identifying optimal forage particle size to enhance growth and development continues to be an important challenge.

Different NDF sources and particle sizes in starter feeds for young ruminants produce varying effects on performance, rumen fermentation, and rumen development. Based on current research, two key points emerge: (1) While controversy persists regarding whether FNDF can improve pre- and post-weaning performance, forage increases rumen pH and buffering capacity, and its physical properties promote muscle layer development and motility, maintaining rumen health and wall integrity. Therefore, appropriate forage inclusion in starter feeds benefits growth and development. (2) The role of NFFS as an NDF source requires further investigation. Within certain ranges, longer-cut forage promotes rumen development and improves performance, with particle size effects interacting with inclusion level. Future research should explore optimal NDF source and particle size for pre-weaning diets, considering their combined nutritional regulation to formulate high-quality starter feeds that promote early growth and development, laying the foundation for optimal adult production performance.

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Note: Figure translations are in progress. See original paper for figures.