Effects of Different Solid-to-Liquid Ratio Feeding Regimens on Nutrient Metabolism and Rumen Fermentation in Pre- and Post-Weaning Calves (Postprint)

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Abstract

This study aimed to investigate the differences in nutrient metabolism and rumen fermentation of calves before and after weaning under different solid-to-liquid feeding ratios, thereby exploring weaning strategies for calves based on different feeding modes. Thirty-six 7-day-old Holstein bull calves were selected and randomly divided into 3 groups. All groups were fed milk replacer and pellet feed with identical ingredient composition and nutritional content. While maintaining consistent total dry matter intake, the solid-to-liquid feed ratio was altered to establish three feeding mode groups: High liquid feed ratio (HL) group: from 28 to 56 days of age, the pellet:milk replacer ratio was maintained at 1:2, with weaning at 56 days; Control (LS) group: from 28 to 56 days of age, the pellet:milk replacer ratio was gradually reduced from 1:2 to 1:1, with weaning at 56 days; High solid feed ratio (HS) group: from 28 to 42 days of age, the pellet:milk replacer ratio was reduced from 1:2 to 1:0, with weaning at 42 days. The experimental period lasted 77 days. Rumen fluid was collected at 28, 42, 56, and 84 days of age, and digestion-metabolism trials were conducted at 35 and 63 days of age (before and after weaning). Results showed: Before weaning, compared with the HS group, the gross energy metabolic rate of calves in the HL and LS groups was relatively higher, but the difference was not significant ($P>0.05$); After weaning, the digestible energy metabolic rate, nitrogen utilization efficiency, and biological value of nitrogen in the HS group were significantly higher than those in the HL group ($P<0.05$). Compared with the HL group, the microbial protein content in rumen fluid at 84 days of age was significantly higher in the HS group ($P<0.05$). No significant differences were observed in rumen fluid ammonia nitrogen concentration among the three groups ($P>0.05$). At 84 days of age, the total volatile fatty acid concentration and butyrate pro-

portion in rumen fluid of calves in the HS group were significantly higher than those in the HL group (P<0.05), while no significant differences were found in propionate or valerate proportions among groups (P>0.05). In conclusion, appropriately increasing the solid feed ratio helps improve the rumen fermentation environment before and after weaning, promotes rumen microbial protein synthesis, and enhances dietary energy metabolic rate, biological value of nitrogen, and nitrogen utilization efficiency in calves after weaning. Adopting a high solid feed feeding mode and implementing weaning when calves reach a solid feed intake of 1.0 kg/d at 42 days of age offers certain advantages. This improves the digestion and utilization efficiency of nutrients in the diet.

Full Text

Effects of Different Feed Patterns of Solid and Liquid Feed Ratios on Nutrient Metabolism and Rumen Fermentation of Pre- and Post-Weaning Calves

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Abstract

This experiment was conducted to investigate the effects of different feeding patterns with varying solid-to-liquid feed ratios on nutrient metabolism and rumen fermentation in pre- and post-weaning calves, thereby exploring weaning strategies based on different feeding patterns. Thirty-six Holstein bull calves at 7 days of age were randomly assigned to three groups (12 calves per group). All groups received milk replacer and starter pellets with identical ingredient composition and nutritional content. Under consistent total dry matter intake, three feeding patterns were established by altering the solid-to-liquid feed ratio: the high liquid feed ratio (HL) group maintained a pellet-to-milk replacer ratio of 1:2 from 28 to 56 days of age and was weaned at 56 days; the control (LS) group gradually decreased the pellet-to-milk replacer ratio from 1:2 to 1:1 during 28 to 56 days of age and was weaned at 56 days; and the high solid feed ratio (HS) group decreased the pellet-to-milk replacer ratio from 1:2 to 1:0 during 28 to 42 days of age and was weaned at 42 days. The experimental period lasted 77 days. Rumen fluid was collected at 28, 42, 56, and 84 days of age, and digestion-metabolism trials were conducted at 35 and 63 days of age. The results showed that pre-weaning, the gross energy metabolizability of calves in HL and LS groups was relatively higher compared with the HS group,

though the difference was not significant (P>0.05). Post-weaning, the HS group exhibited significantly improved digestible energy metabolizability, nitrogen utilization, and nitrogen biological value compared with the HL group (P<0.05). Microbial protein content in rumen fluid at 84 days of age was significantly higher in the HS group than in the HL group (P<0.05). No significant differences were observed in rumen fluid ammonia nitrogen concentration among the three groups (P>0.05). At 84 days of age, total volatile fatty acid concentration and butyrate proportion in the HS group were significantly higher than those in the HL group (P<0.05), while propionate and valerate proportions showed no significant differences among groups (P>0.05). In conclusion, appropriately increasing the solid feed ratio helps improve rumen fermentation environment in pre- and post-weaning calves, promotes rumen microbial protein synthesis, and enhances dietary energy metabolizability, nitrogen biological value, and nitrogen utilization post-weaning. Implementing a high solid feed feeding pattern and weaning calves at 42 days of age when solid feed intake reaches 1.0 kg/d offers certain advantages.

Keywords: calf; solid and liquid feed ratio; microbial protein; nutrient metabolism; rumen fermentation

Introduction

Nutrient absorption and utilization interact with rumen development, both of which significantly affect calf performance during the calf stage and throughout adulthood. As the primary source of nutrients for animals, feed composition and physical form are crucial for rumen development in calves. Calf feed includes two forms: liquid and solid. Liquid feed primarily comprises fresh milk and milk replacer. When calves consume liquid feed, the esophageal groove closes reflexively, directing milk directly into the abomasum where it forms curds that are digested by enzymes and absorbed in the intestine, providing the main nutrients for pre-weaning calves. Solid feed enters the rumen directly, participating in rumen growth and development through a series of processes including solid feed intake stimulation, microbial fermentation system maturation, and coordination of fermentation and absorption mechanisms. Volatile fatty acids (VFA) produced through fermentation in the rumen directly stimulate rumen development and serve as a prerequisite for good nutrient metabolism in post-weaning calves and adult cattle. Therefore, different relative feeding amounts of solid and liquid feed affect calf growth and development.

Research indicates that insufficient solid feed intake can lead to incomplete rumen keratinization, delayed development, and ultimately impaired nutrient absorption. Increased solid feed intake in calves can accelerate rumen fermentation rate and extent, as well as VFA absorption and metabolism. Conversely, insufficient liquid feed intake can cause diseases such as abomasal lesions. Early weaning in calves is closely related to solid and liquid feed intake. The general

rule in large-scale dairy farms in China is to wean calves when solid feed intake reaches 1.0 kg/d for three consecutive days, or to wean calves at approximately 8 weeks of liquid feeding. However, these feeding patterns still cause weaning stress in calves, leading to disease, growth retardation, production losses, and hindering early rearing of replacement heifers. Therefore, this experiment maintained consistent total dry matter intake (DMI) while altering solid-to-liquid feed ratios to create different weaning methods, aiming to investigate the effects of different solid-liquid ratio feeding patterns on energy and nitrogen metabolism, rumen microbial protein (MCP) synthesis, and rumen fermentation in pre- and post-weaning calves, thereby providing theoretical support for rational solid-liquid feed ratios and weaning methods in calf rearing.

1.1 Experimental Time and Location

The animal feeding trial was conducted from September to December 2015 at the pilot base of the Chinese Academy of Agricultural Sciences. The experimental period lasted 77 days.

1.2 Experimental Design

Thirty-six naturally delivered Holstein bull calves with birth weight of $(36.0\$\pm2.5)kgandadequatecolostrumintakewereselectedat(7\pm\$2)$ days of age. A single-factor randomized design was employed, with calves randomly divided into three groups of 12 animals each. All calves began consuming liquid milk replacer at 7 days of age, were trained to consume solid starter pellets at 21 days, and underwent a transition period from 21 to 27 days. At 28 days of age, milk replacer DMI was set at 1.2% of body weight, and pellet intake reached 200 g/d.

The control (LS) group followed current large-scale farm feeding protocols, with solid pellet intake increasing by 200 g/d weekly and liquid feed intake at 12.5% of body weight, adjusted gradually with body weight growth. During 28 to 56 days of age, the solid pellet-to-liquid feed ratio decreased from 1:2 to 1:1. Calves were weaned at 56 days of age when solid feed intake reached approximately 1 kg/d.

The high liquid feed ratio (HL) group was fed primarily liquid milk replacer, with total DMI consistent with the LS group but solid pellet intake increasing by only 100 g/d weekly, with the remainder as liquid feed. During 28 to 56 days of age, the solid pellet-to-liquid feed ratio was maintained at 1:2. Calves were weaned at 56 days of age when solid feed intake was only approximately 0.6 kg/d.

The high solid feed ratio (HS) group was fed primarily solid starter pellets, with total DMI consistent with the LS group but solid pellet intake increasing by 400 g/d weekly, with the remainder as liquid feed. During 28 to 42 days of age, the solid pellet-to-liquid feed ratio decreased from 1:2 to 1:0. Calves were weaned at 42 days of age when solid feed intake reached approximately 1.0 kg/d.

The milk replacer and starter pellets were produced using formula ZL201210366241.9, with nutritional levels (on a dry matter basis) of: DM 95.13%, organic matter (OM) 91.81%, crude protein (CP) 21.88%, ether extract (EE) 12.17%, neutral detergent fiber (NDF) 4.03%, acid detergent fiber (ADF) 2.29%, calcium (Ca) 1.17%, phosphorus (P) 0.58%, and gross energy (GE) 18.49 MJ/kg. The milk replacer was in powder form, and pellets were processed at 50°C with a diameter of 8 mm.

1.3 Feeding Management

Milk replacer emulsion was prepared by mixing with boiled water cooled to 50-60°C at a DM concentration of 12.5%, then fed to calves when the temperature dropped to approximately 40°C. Feeding occurred twice daily (08:00 and 16:00) using nipple-equipped hanging buckets.

Calves were individually housed in calf hutches, each occupying an area of 1.6 m × 3.6 m. Feed supply during the trial period was calculated based on individual calf intake. Clean and adequate water was provided.

1.4 Digestion-Metabolism Trials

Six healthy calves with body weight close to the group average were selected from each group for total feces and urine collection using digestion-metabolism cages (patent number ZL201420358189.7) at pre-weaning (35 days) and post-weaning (63 days) stages. The trial period was 7 days, including a 3-day preliminary period and a 4-day formal collection period. Daily feed intake, fecal output, and urine output were recorded, and fecal and urine samples were collected.

1.5 Sample Analysis

1.5.1 Feed Samples Representative feed samples were collected during the experiment. Nutritional components were determined according to AOAC (2000) methods: CP content was measured using a KDY-9830 automatic Kjeldahl nitrogen analyzer; EE content was determined using an ANKOM-XT15i automatic fat analyzer; GE was measured using a PARR-6400 automatic bomb calorimeter. OM, NDF, ADF, Ca, and P contents were determined using the method of Zhang Liying.

1.5.2 Digestion-Metabolism Trial Samples During the formal collection period, 10% of the total daily feces was collected as a composite sample, with 10 mL of 10% dilute sulfuric acid added per 100 g fresh feces for nitrogen fixation. One percent of the daily urine output was continuously collected, with 10% dilute sulfuric acid added to adjust pH to $ $3. Representative feed samples were collected daily. Collected feed, fecal, and urine samples were stored at -20°C for subsequent analysis. Determination of DM and CP content and GE in diet samples, DM and CP content and fecal energy and nitrogen excretion in fecal samples, and urine energy and nitrogen excretion in urine samples

followed AOAC (2001) methods using the aforementioned instruments. Dietary digestible energy, metabolizable energy, apparent digestibility of GE, metabolizability of GE, and metabolizability of digestible energy were calculated using the following formulas:

Digestible energy = GE intake - fecal energy
Metabolizable energy = GE intake - fecal energy - urine energy - methane energy
Apparent digestibility of GE = Digestible energy / GE intake
Metabolizability of GE = Metabolizable energy / GE intake
Metabolizability of digestible energy = Metabolizable energy / Digestible energy

Methane energy was calculated as 8% of GE intake.

1.5.3 Rumen Fluid Samples Six calves with body weight close to the group average were selected from each group. Rumen contents (100 mL) were collected using sterilized oral tubes at 2 hours post-feeding on days 28, 42, 56, and 84, filtered through 4 layers of gauze, and immediately measured for pH using a portable pH meter (testo-206-ph2). Samples were then aliquoted into 10 mL sterilized centrifuge tubes, transported in liquid nitrogen, and stored at -80°C for analysis.

Rumen fluid was thawed at 4°C, and 1 mL of supernatant was mixed with 0.3 mL of 25% metaphosphoric acid, vortexed for 3-5 seconds, left to stand for 30 minutes, and centrifuged at 15,000×g for 15 minutes. The supernatant (0.5 mL) was collected. VFA concentration in rumen fluid was determined according to Cao et al.; ammonia nitrogen (NH3-N) concentration was measured using the indophenol method; MCP content was determined according to Makkar et al.

1.6 Statistical Analysis

Data were analyzed using SAS 9.2 software. Except for energy and nitrogen data from digestion-metabolism trials, which were analyzed using one-way ANOVA, other data were analyzed using the MIXED model. When significant differences were detected ($P<0.05$), the least significant difference (LSD) method was used for comparison.

The one-way ANOVA model was:

$Yij = \quad + Ti + \ ij$

Where: is the overall mean; T is group (i=1,2,3) as a fixed effect; is the residual; j=1,2,3,⋯,12 (calves).

The MIXED model was:

$Yijk = \quad + Ti + Dj + TDij + C(T)ik + \ ijk$

Where: is the overall mean; T is group (i=1,2,3) as a fixed effect; D is day of age (j=35,63) as a fixed effect; C is calf (k=1,2,3,⋯,12) as a random effect; is the residual.

2.1 Calf Feed Intake

As shown in , different solid-liquid ratios had no significant effect on total DMI of calves pre-weaning (P>0.05). Post-weaning, total DMI of calves in the HL group was significantly lower than in the other two groups (P<0.05).

2.2 Calf Energy Metabolism

As shown in , pre-weaning, the HL feeding pattern tended to reduce fecal energy compared with the LS group (P=0.081), while GE apparent digestibility was significantly increased in the HL group (P<0.05). Post-weaning, compared with the HL group, the HS group significantly improved digestible energy metabolizability (P<0.05) by significantly reducing urine energy (P<0.05), while no significant difference in digestible energy metabolizability was observed between LS and HL groups (P>0.05).

2.3 Calf Nitrogen Digestion and Metabolism

As shown in , pre-weaning, the HL group significantly improved nitrogen utilization and retained nitrogen compared with LS and HS groups (P<0.05). Post-weaning, HS and LS groups significantly improved nitrogen retention and nitrogen utilization compared with the HL group (P<0.05) by reducing urine nitrogen excretion (P=0.073) and total nitrogen excretion (P<0.05). Additionally, the biological value of nitrogen in post-weaning calves was significantly higher in the HS group than in the HL group (P<0.05), with no significant difference from the LS group (P>0.05). However, no significant differences were observed in urine nitrogen excretion and absorbed nitrogen among the three groups pre- and post-weaning (P>0.05).

2.4 Rumen Fluid pH, NH3-N Concentration, and MCP Content

As shown in , the HS feeding pattern resulted in lower rumen fluid pH in calves, with a tendency to be lower than HL and LS groups at 56 days of age (P=0.061), and significantly lower than the HL group at 84 days of age (P<0.05). Compared with HL and HS groups, NH3-N concentration in rumen fluid tended to be higher in the LS group at 42 days of age (P=0.099). MCP content in rumen fluid increased significantly with calf age (P<0.05), with differences observed among groups post-weaning. At 56 days of age, HS and LS groups tended to be higher than the HL group (P=0.051), and at 84 days of age, the HS group was significantly higher than the HL group (P<0.05).

2.5 Rumen Fluid VFA Content

As shown in , different feeding patterns affected rumen fluid VFA content in post-weaning calves, with total volatile fatty acid (TVFA) concentration increasing significantly with calf age (P<0.05). At 56 days of age, TVFA concentration in the HS group tended to be higher than in the LS group (P=0.087), and at

84 days of age, HS and LS groups were significantly higher than the HL group ($P<0.05$), with no significant differences among groups at other ages ($P>0.05$). At 56 days of age, acetate proportion in the LS group tended to be lower than in other groups ($P=0.082$). At 84 days of age, acetate, butyrate proportions, and acetate/propionate ratio in the HS group were significantly higher than in the other two groups ($P<0.05$). Valerate proportion was not affected by feeding pattern pre- or post-weaning ($P>0.05$).

3.1 Effects of Different Solid-Liquid Ratio Feeding Patterns on Energy and Nitrogen Digestion-Metabolism in Calves

Gastrointestinal digestion, utilization, and absorption of nutrients from solid and liquid feeds directly affect calf growth performance during pre- and post-weaning periods. Studies by Jasper et al. and Anderson et al. found that increased liquid feed intake improved apparent nutrient digestibility pre-weaning, while solid pellet supplementation enhanced apparent nutrient digestibility post-weaning. In this experiment, total DMI did not differ significantly among groups pre-weaning, while GE apparent digestibility and nitrogen utilization were higher in the HL group, consistent with Khan et al. During this stage, calf nutrient digestion and absorption relied heavily on the abomasum. Higher liquid feed intake and prolonged duration resulted in large amounts of liquid feed reaching the abomasum, where rennet, protease, and amylase secreted by the abomasum digested and absorbed the liquid feed. Additionally, endocrine hormones related to liquid nutrient absorption, such as insulin and insulin-like growth factor 1, could stimulate local intestinal responses and enhance intestinal absorption, thereby improving nutrient metabolizable energy. During this period, the rumen was not yet developed, and nutrients from solid feed reaching the rumen could not be fully absorbed, resulting in lower digestible energy under high solid feed feeding. Regarding nitrogen digestion and utilization, increased liquid milk replacer feeding significantly improved retained nitrogen and nitrogen utilization in pre-weaning calves, consistent with Xu et al.

Post-weaning, solid feed intake positively promoted calf feed intake. Di Giancamillo et al. found that calves fed solid feed spent most of their time eating and ruminating, while calves fed only liquid feed spent most of their time licking any accessible objects. Therefore, adequate solid feed intake could promote increased DMI in post-weaning calves. This experiment also showed that DMI in post-weaning calves was significantly increased under the high solid ratio feeding pattern. Additionally, post-weaning, the rumen assumed primary digestive functions. Higher solid feed intake during the nursing period resulted in more developed rumen, significantly increased feed intake, and improved carbohydrate digestion and absorption through stimulation of gastrointestinal digestive enzyme secretion or enhanced enzyme activity, thereby reducing urine energy and improving GE apparent digestibility and GE metabolizability. This experiment also demonstrated that feeding high proportions of solid feed during the nursing period reduced total nitrogen excretion and increased retained nitrogen,

nitrogen utilization, and nitrogen biological value post-weaning (63-84 days of age). The possible reason is that better solid feed digestion and absorption promoted gastrointestinal microbial development, which improved gastrointestinal metabolic activity. Combined with changes in MCP content post-weaning, the reason may be that solid feed increased the number of various protein-degrading bacteria in the gastrointestinal tract, enabling more dietary CP to be degraded and synthesized into MCP. Gastrointestinal digestive enzyme activity was also higher, and interactions among various digestive enzymes and metabolites improved amino acid balance, thereby increasing nitrogen utilization and reducing nitrogen excretion in feces and urine. Based on energy and nitrogen digestion-metabolism results, high solid ratio feeding promoted energy and nitrogen utilization in calves post-weaning.

3.2 Effects of Different Solid-Liquid Ratio Feeding Patterns on Rumen Fermentation in Calves

Rumen fluid pH, NH3-N, and VFA concentrations are important indicators of rumen fermentation in ruminants, reflecting rumen function and stability of the rumen internal environment. This experiment showed that increasing solid feed intake in pre-weaning calves reduced rumen fluid pH pre- and post-weaning, consistent with Ren' s study on feeding patterns and rumen fluid pH in calves. Solid feed accumulated in the rumen and fermented to produce acids, thereby reducing rumen fluid pH. Rumen fluid pH does not directly affect rumen development, but Krehbiel et al. found that it could alter butyrate proportion in rumen fluid, causing changes in VFA proportions. As the optimal stimulant for rumen development, butyrate absorption also increased with decreasing rumen fluid pH. Rumen fluid pH directly affects rumen epithelial cell absorption and metabolism of VFA, thereby indirectly influencing rumen development. Within the normal physiological range, increased propionate and butyrate concentrations not only result in lower rumen fluid pH but also enhance their absorption by rumen epithelium, which benefits rapid rumen development in calves.

NH3-N concentration in rumen fluid is the primary condition ensuring efficient MCP synthesis, and its dynamic changes reflect the dynamic balance between protein degradation and MCP synthesis in the rumen. An NH3-N concentration of 2 mmol/L in rumen fluid can meet the needs of rumen microbial protein synthesis. In this experiment, rumen fluid NH3-N concentration ranged from 2.47 to 7.00 mmol/L, which meets the growth conditions for rumen microorganisms, and NH3-N concentration in post-weaning calves was significantly lower than pre-weaning, consistent with Anderson et al. The rumen function of newborn calves is not fully developed. With increasing age, rumen maturation and gradual establishment of microbial flora result in rumen microorganisms converting more NH3-N to MCP during proliferation, reducing NH3-N concentration. This explains the phenomenon of increasing MCP content in rumen fluid with calf age. Rumen MCP can provide 50-80% of small intestine absorbable protein for ruminants, and its synthesis in the rumen is mainly related to microbially avail-

able energy and protein. Increasing the solid feed ratio enhanced MCP synthesis in post-weaning calves, indicating that this feeding pattern could promote rumen microbial utilization of dietary energy and protein, consistent with changes in energy and nitrogen metabolism in this experiment and confirming its role in improving nutrient digestion and utilization in calves. This demonstrates that increasing the solid feed ratio improved rumen microbial utilization of dietary protein while having no effect on rumen fluid NH3-N concentration.

3.3 Effects of Different Solid-Liquid Ratio Feeding Patterns on Rumen Fermentation Products in Calves

This experiment found that TVFA concentration in rumen fluid increased significantly with calf age, consistent with Zhang et al. Acetate, propionate, and butyrate were the main components. VFA, as important products of carbohydrate fermentation in the rumen, have concentrations determined by fermentation yield, fermentation rate, rumen epithelial absorption rate, and rumen emptying rate, and serve as important indicators of rumen development maturity. Their metabolism also reflects rumen epithelial cell development level. The short-chain fatty acid metabolism level of 30-day-old calves is equivalent to 40% of adult cattle, while that of 60-day-old calves approaches adult levels, indicating that VFA in the rumen of calves gradually increase with age before 60 days. VFA are key factors stimulating rumen development. With increasing solid feed intake, rumen function gradually matures, and rumen fermentation status gradually improves post-weaning. At 84 days of age, TVFA concentration in calves fed high solid ratio feed reached 54.29 mmol/L, with acetate, propionate proportions, and TVFA concentration increasing by 33.36%, 48.41%, and 40.10%, respectively, compared with calves fed high liquid ratio feed. This is consistent with Ghorbani et al., who significantly increased rumen fluid TVFA concentration by limiting liquid intake to increase solid feed intake. This occurs because solid feed feeding provides not only necessary chemical stimulation for the rumen but also certain physical stimulation, ultimately promoting VFA production or concentration increase. Acetate is decomposed into CO2 and H2O during the tricarboxylic acid cycle, releasing ATP to supply energy. Propionate, as the only glucogenic VFA, acts in the gluconeogenesis process, promoting efficient utilization of dietary nutrients. Additionally, under high solid feed feeding patterns, butyrate proportion also increased significantly and continued to grow post-weaning. During absorption through the rumen-reticulum wall, most butyrate is converted to β-hydroxybutyrate as an energy source for several body tissues, especially muscle tissue. Butyrate is also crucial for rumen development in young ruminants, as it not only promotes rumen epithelial cell proliferation and differentiation but also improves gastrointestinal sensitivity and promotes intestinal motility. Under solid feed stimulation, microbial interactions in the rumen stimulate rapid microbial reproduction, substantially increasing butyrate proportion, which explains the reduced rumen pH in calves fed high solid feed.

Solid feed intake status affects nutrient absorption and metabolism through-

out the entire growth period, especially post-weaning. Wu et al. showed that feeding dairy bull calves with solid pellets instead of part of the milk replacer promoted healthy growth. In this experiment, high proportions of solid feed entering the calf rumen produced more volatile fatty acids through fermentation, improved the rumen fermentation environment, stimulated foregut development, especially rumen development, and thereby improved energy and nitrogen utilization in nutrients, reducing nutrient loss.

In conclusion, appropriately increasing the solid feed feeding ratio helps improve rumen fermentation in pre- and post-weaning calves, promotes rumen MCP synthesis, and enhances dietary energy metabolizability, nitrogen biological value, and nitrogen utilization post-weaning. Adopting a high solid feed feeding pattern and implementing weaning at 42 days of age when solid feed intake reaches 1.0 kg/d offers certain advantages.

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