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Anjali Arya
Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Anand, Gujarat, India

PM Lunagariya
Livestock Research Station, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Anand, Gujarat, India

RJ Modi
Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Anand, Gujarat, India

YG Patel
Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Anand, Gujarat, India

Corresponding Author:
Anjali Arya
Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Kamdhenu University, Anand, Gujarat, India

Rumen fermentation

Anjali Arya, PM Lunagariya, RJ Modi and YG Patel

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Abstract
The rumen is a complex anaerobic ecosystem where microorganisms, including bacteria, protozoa, and fungi, digest nutrients, producing volatile fatty acids (VFAs) and microbial biomass, which are utilized by ruminants. This symbiotic relationship facilitates the conversion of fibrous diets into meat, milk, and fibers. Environmental factors such as temperature (39 to 41 °C), pH (5.5 to 7.0), and osmotic pressure (250 to 400 mOsm/kg) are essential for maintaining microbial populations and their digestive activities. Carbohydrate fermentation in the rumen yields VFAs-acetate, propionate, and butyrate-that serve as crucial energy sources, while protein digestion involves microbial synthesis of amino acids, and fats provide additional energy and essential fatty acids, ensuring efficient nutrient utilization and supporting ruminant health and productivity.

Keywords: Rumen, volatile fatty acids, fermentation, productivity

Introduction

The rumen represents a complex anaerobic ecosystem where microorganisms, including bacteria, protozoa, and fungi, digest ingested nutrients. The primary end products of this fermentation process are volatile fatty acids (VFAs) and microbial biomass, which are utilized by the host ruminant. This symbiotic relationship enables ruminants to efficiently digest high-fiber, low-protein diets. The rumen environment promotes microbial activity, facilitating the production of enzymes essential for nutrient digestion. Consequently, ruminants can convert low-quality fibrous materials into valuable products such as meat, milk, and fibers, benefiting human use. Ruminants can efficiently obtain energy from forages due to the enzymatic activity of ruminal microbes (Burns, 2008) [1]. However, ruminal fermentation is not totally efficient, creating by-products such as methane (Kingston-Smith *et al*., 2012) [4] and excess ammonia (Russell and Mantovani, 2002) [6].

The enzymatic activity of ruminal microorganisms enables ruminants to derive energy from forages efficiently (Burns, 2008) [1]. However, ruminal fermentation is not entirely efficient, producing by-products such as methane (Kingston-Smith *et al*., 2012) [4] and excess ammonia (Russell and Mantovani, 2002) [6]. Cattle, sheep, and goats are examples of ruminants that have evolved to effectively utilise fibrous diets. Because ruminal microorganisms synthesise necessary amino acids (Cole *et al*., 1982) [3] and vitamin B complex (Russell and Mantovani, 2002) [6], their digestive system's anatomical adaptations enable them to use cellulose as an energy source. The rumen's symbiotic interaction creates a favourable environment for the establishment of microbes and the upkeep of substrate. The bacteria facilitate the production of energy by providing the host ruminant with nutrients in exchange.

Physicochemical properties of the Rumen

The ruminant digestive system consists of the reticulum, rumen, omasum, and abomasum, with the rumen serving as the primary site for fermentation. Microorganisms in the rumen produce enzymes essential for the digestion and fermentation of ingested feed, rendering the rumen an effective fermentation vat. The growth and activity of ruminal microbial populations are influenced by several physicochemical factors, including temperature, pH, buffering capacity, osmotic pressure, and redox potential, all of which are dictated by environmental conditions.

The temperature range of the rumen is 39 to 39.5 °C, and because of the exothermic nature of fermentation, it can increase to 41 °C after feeding. The creation and absorption of short-chain fatty acids (SCFAs), feed type and intake amount, saliva production, and the exchange of bicarbonates and phosphates through the ruminal epithelium all influence the rumen pH. Rumen pH usually varies but stays between 5.5 and 7.0 depending on food and salivary buffering ability. With a pH of 8.2, saliva continuously supplies phosphates and bicarbonates, which helps the rumen maintain its buffering ability. Cruciferous secretions also have inherent buffering properties (Krause and Oetzel, 2006) [5].

Microbial intracellular pH usually stabilizes around 7.0 but can significantly drop in acidic conditions, inhibiting bacterial growth due to intracellular hydrogen ion imbalance. Rumen osmotic pressure, influenced by ion and molecule concentrations, typically measures around 250 mOsm/kg. Post-feeding, osmotic pressure can rise to 350-400 mOsm, subsequently decreasing over 8 to 10 hours. The osmotic pressure is affected by the presence of VFAs produced during fermentation and correlates directly with dietary carbohydrate content and resulting pH variations. These physicochemical properties collectively create an optimal environment for microbial activity, facilitating efficient nutrient digestion and absorption within the rumen.

Microbes of the Rumen and the Reticulum

The ruminal ecosystem is made up of a wide variety of microorganisms living in a strictly anaerobic environment in symbiotic relationships. The ruminal bacteria, protozoa, and fungus that make up this microbiota have corresponding cell counts of 1010, 106, and 104/ml. The ruminants' forages are broken down by these microbes into fermentation products, which are then used by the microbes for growth and reproduction as well as by the host animal. Protozoa and bacteria are the most common microorganisms found in the rumen; billions of them are in charge of breaking down between 70% and 80% of the dry materials that can be digested. Different types of bacteria and protozoa play different roles. For example, some are good at breaking down cellulose, while others are specialised in the digestion of starch and sugar. The animal's diet affects the number and makeup of these microbial species, and a balanced microbial population is essential for the best possible rumen function. The primary end products of microbial fermentation include:

Volatile fatty acids (VFAs): These are the main products of fermentation and serve as the principal energy source for the ruminant.

Ammonia: This is utilized in the synthesis of microbial protein. Given that bacteria consist of approximately 60% protein, they constitute a major protein source for the ruminant as they exit the rumen and are subsequently digested in the abomasum and small intestine.

Gases: These are by-products of fermentation that represent wasted energy, as they are expelled through belching.

Rate of Digestion

Along with a number of other criteria, the quality and composition of the feed have an impact on how quickly feed is absorbed in the rumen. The rumen's pH level, the quantity and kind of microorganisms present, the availability of nutrients necessary for microbial growth, and the elimination of microbes from the rumen are a few of these. The main nutrients that restrict microbial growth and, in turn, rumen fermentation are energy and protein. For development and replication, the microbial population needs an adequate supply of both energy and protein. A shortage of any one of these nutrients slows down the proliferation of microorganisms, which lowers the digestibility (or rate at which feed breaks down).

Carbohydrate Digestion in the Rumen

Upon ingestion by ruminants, nutrients such as carbohydrates, proteins, and lipids are initially present in their complex forms. These nutrients undergo digestion, transforming into simpler products that can be directly utilized by the animal or the microbes within the rumen. Approximately 75% of plant tissue dry matter is composed of carbohydrates. Through microbial fermentation, these carbohydrates are broken down into simple sugars, which serve as an energy source for microbial growth, resulting in end products that the animal can utilize.

The primary end products of microbial fermentation of carbohydrates include:

Volatile fatty acids (VFAs): mainly acetate, propionate, and butyrate.

Gases: such as carbon dioxide and methane.

All types of carbohydrates are fermented by rumen microorganisms, although soluble and storage carbohydrates are fermented more quickly than structural carbs. Cell wall material digests more slowly than sugars and starches, which break down easily and quickly. As plants develop, their cell walls get lignified, limiting the availability and utilization of structural carbohydrates. As a result of the reduced accessibility and harder time breaking down cell wall components, plants become less digestible as they mature. Rumen microorganisms break down soluble carbs roughly 100 times more quickly than storing carbohydrates, which break down roughly five times more quickly than structural carbohydrates.

Structural Carbohydrates

Bacteria that digest structural carbohydrates, such as cellulose and hemicellulose, produce a significant amount of acetic acid, which is essential for milk fat synthesis. These cellulolytic bacteria are highly sensitive to the presence of fats and acidic conditions within the rumen. Excessive dietary fat or increased ruminal acidity, often resulting from the consumption of rapidly digestible carbohydrates, can severely inhibit or eliminate these bacterial populations. The reduction or elimination of cellulolytic bacteria not only diminishes the digestibility of the feed but may also decrease the animal's feed intake. Structural carbohydrates that transit the rumen without adequate microbial breakdown are unlikely to undergo further digestion in subsequent sections of the digestive tract.

Storage Carbohydrates

Bacteria that digest starchy feeds, such as cereal grains or potatoes, differ from cellulose-digesting bacteria. These amylolytic bacteria are resistant to acidic conditions and predominantly produce propionic acid. Starches undergo rapid fermentation, and the resulting lactic and propionic acids contribute to increased ruminal acidity. This elevated acidity can inhibit the activity of cellulolytic bacteria, subsequently reducing the digestion of cellulose and leading to a decrease in milk fat levels.

Soluble Sugars

Similar to those that ferment starch, these bacteria also ferment feeds rich in soluble sugars, like molasses, sugar cane, and premium grass. In general, higher ruminal acidity problems are less common with sugary feeds than with starchy feeds. But in order to avoid upset stomachs, sweet foods have to be added to the ruminant's diet gradually.

The Products of Carbohydrate Digestion

Volatile Fatty Acids

The primary end products of carbohydrate fermentation in the rumen are Volatile Fatty Acids (VFAs). These VFAs play critical roles:

- They constitute the predominant (70%) energy source for ruminants.
- Their relative proportions influence the fat and protein composition of milk.

The major VFAs produced include acetate (acetic acid), propionate (propionic acid), and butyrate (butyric acid). The specific ratio of these VFAs depends on the composition of the ingested feed. VFAs are absorbed across the rumen epithelium and subsequently transported via the bloodstream to the liver (Fig. 1). Within the liver, VFAs are metabolized into alternative energy sources, which support various physiological functions such as milk synthesis, body maintenance, pregnancy, and growth.

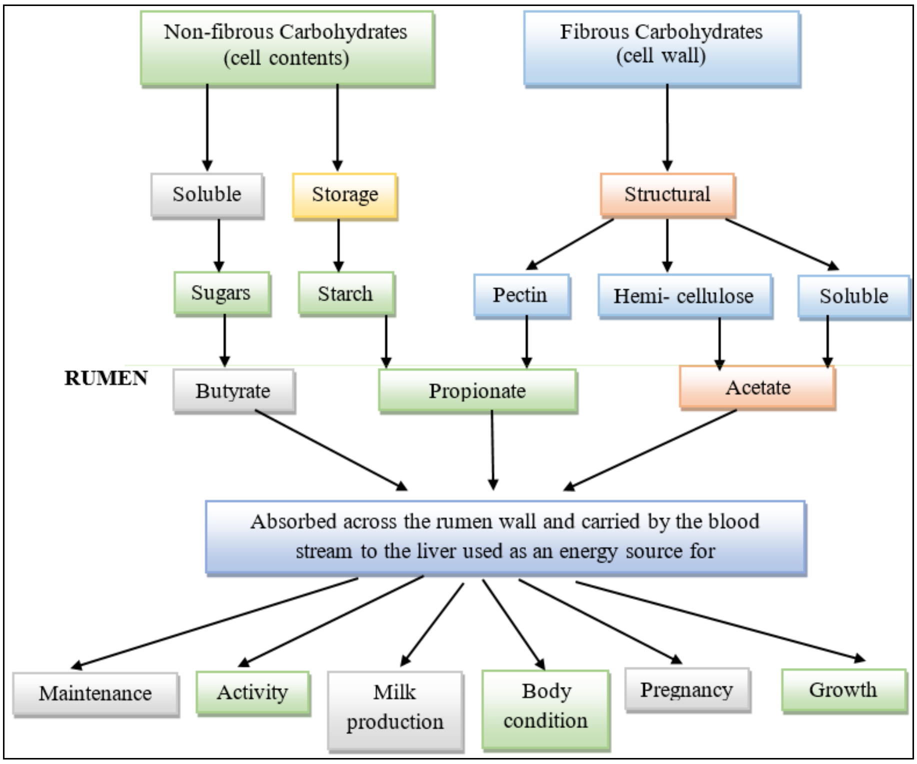

Fig 1: Digestion of carbohydrates, and production and absorption of volatile fatty acids

Acetate

Acetate is synthesized as an end product during the fermentation of fiber-rich feeds. Diets composed primarily of highly fibrous and low-energy sources like pasture hay promote microbial communities that generate high ratios of acetate to propionate. Acetate is crucial for milk fat synthesis. Conversely, diets rich in grains (low in fiber) result in reduced acetate production, potentially leading to a decrease in milk fat production.

Propionate

Propionate is a product of the fermentation process involving starch and sugars. It serves as a primary energy source for enhancing live weight gain and facilitating lactose production in the mammary system. Diets rich in quickly fermentable carbohydrates, such as cereal grains, foster bacterial populations that yield relatively higher proportions of propionate and butyrate compared to acetate. Propionate is valued for its efficiency in energy utilization, as fermentations favoring propionate production emit less methane and carbon dioxide. Inadequate propionate production, common in high-fiber diets, diminishes milk lactose synthesis and overall milk yield. To compensate for this energy shortfall, the animal mobilizes body fat, leading to a decline in body condition.

Butyrate

Butyrate undergoes metabolism in the liver, where it is converted into ketone bodies. These ketone bodies serve as crucial energy sources for synthesizing fatty acids, supporting skeletal muscles, and maintaining various body tissues. Additionally, ketone bodies are generated through the mobilization of body fat. In instances where cows experience underfeeding during early lactation, leading to a loss of body condition due to insufficient dietary energy, ketone bodies are utilized as alternative energy substrates.

Gas

During carbohydrate fermentation in the rumen, carbon dioxide and methane are byproducts. These gases are eliminated either through diffusion across the rumen wall or released via eructation (belching). A portion of carbon dioxide is utilized by intestinal microbes and the cow to regulate bicarbonate levels in saliva. However, methane cannot be utilized by the ruminant's metabolic processes as an energy source.

Digestion of Protein

Protein undergoes digestion in the rumen, where it is initially broken down into peptides, which are short chains composed of amino acids. Subsequent digestion of peptides results in the release of individual amino acids and ultimately ammonia. The protein utilized by the cow originates from both the feed consumed and from the microbes that are washed out from the rumen. The proportion of each depends on the extent to which dietary protein is degraded within the rumen and on the dynamics of microbial growth and outflow from the rumen.

Microbial Protein

Rumen microbes play a pivotal role as the primary source of protein in the ruminant's diet, breaking down Rumen Degradable Protein (RDP) into amino acids and subsequently into ammonia. Ammonia serves as a crucial nitrogen source for microbial growth, which is further supported by the conversion of non-protein nitrogen into ammonia by these microbes. Microbes are continuously removed from the rumen and pass through the omasum to the abomasum, where they are digested by the ruminant. Amino acids derived from microbial protein digestion are absorbed through the small intestine. The quantity of microbial protein reaching the intestines is contingent upon the availability of energy and ammonia in the ruminant's diet. Under conditions of limited energy, microbial efficiency in utilizing ammonia diminishes. Instead of being utilized for microbial protein synthesis, ammonia is absorbed across the rumen wall into the bloodstream and subsequently converted into urea in the liver. While most urea is excreted in urine, some is recycled back into the rumen via saliva as non-protein nitrogen. Conversely, when there is an excess of energy relative to protein, the rate of microbial protein synthesis decreases. This reduction in total protein supply to the cow leads to decreased milk yield and milk protein yield, with surplus energy being deposited as body fat rather than being utilized for milk production. Typically, diets rich in high-quality forage are characterized by relatively ample protein content.

Dietary Protein

The dietary protein accessible to the ruminant consists of Undegradable Dietary Protein (UDP) and rumen degradable protein that has evaded microbial breakdown. These proteins undergo digestion primarily in the abomasum and small intestine. UDP and the fraction of Rumen Degradable Protein (RDP) that escapes microbial fermentation offer a wider array of amino acids compared to those derived solely from microbial proteins broken down in the rumen. This broader diversity encompasses proteins and their constituent amino acids originating from sources beyond ruminal microbes.

Digestion of Fats

Fats serve as an important energy source for ruminants. They undergo partial degradation within the rumen or are provided in a bypass or protected form. Microbial fermentation of fats in the rumen also contributes to the synthesis of essential vitamins needed by the ruminant. While fats are present in various common dairy feeds in relatively modest quantities, their inclusion in the diet should not exceed 5% of the total dry matter intake (approximately 500 g/day). Exceeding this threshold can lead to the coating of dietary fiber in the digestive tract, hindering fiber digestion and reducing diet palatability. Protected fats, which evade microbial breakdown in the rumen, offer a solution to digestive disturbances caused by high levels of rumen-degradable fat. These protected fats are efficiently digested and absorbed across the small intestine wall. Fats derived from oilseeds, such as whole cottonseed, are particularly beneficial as they elevate the energy density of the diet, especially during early lactation, thereby aiding in the prevention of live weight loss.

Conclusion

In conclusion, the rumen acts as a vital anaerobic environment where diverse microbial communities work in harmony with ruminants to digest challenging plant materials efficiently. This symbiotic relationship enables ruminants to extract energy from high-fiber, low-protein diets that would otherwise be inaccessible. The enzymatic processes of ruminal microorganisms produce essential volatile fatty acids and microbial proteins crucial for metabolic functions and milk production. Despite its efficiency, rumen fermentation generates methane and excess ammonia, highlighting the need for careful dietary management to mitigate environmental impacts. Understanding the rumen's physicochemical dynamics and microbial interactions is pivotal for optimizing ruminant nutrition and fostering sustainable livestock production practices.

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