Rumen pH and microbial shift: implications for ruminant nutrition-a review

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Abstract

The microbial ecosystems in foregut of ruminants, encompassing bacteria, ciliate protozoa, anaerobic fungi, bacteriophages, viruses, and methanogens, play a crucial role in the efficient digestion of diverse feed ingredients. In this review paper the intricate symbiotic relationship between the ruminant host and rumen microbes, highlighting the impact of diet composition on rumen pH and microbial diversity were explored. While developed countries rely mostly on the use grains and concentrates to enhance productivity, this approach alters rumen parameters, affecting microbial distribution and overall health. Rumen pH is vital for microbial stability, with fluctuations influencing feed digestibility and animal health. High-grain diets can lead to Sub-Acute Ruminal Acidosis (SARA), impacting fibre-digesting bacteria and causing metabolic disorders. Conversely, low-fibre diets can damage rumen walls, affecting animal health. Fibre-rich diets help maintain optimal rumen conditions. The article discusses the impact on animal health, production, and milk/meat quality, emphasizing the need for a balanced approach in ruminant nutrition. Management strategies, such as balanced diets, gradual diet changes, and feeding frequency adjustments, are crucial for maintaining a healthy rumen environment. Various additives and buffers are employed to stabilize rumen pH. The study also explores the influence of factors like dietary fat, plant phytochemicals, and individual differences on microbial diversity. Understanding the dynamic interaction between rumen pH and microbes is vital for optimizing animal diets, minimizing waste, and ensuring sustainable ruminant production. The study concludes by emphasizing the importance of considering gut anatomy in microbial ecology studies to comprehensively assess the impact of nutrition on ruminant health.

Keywords: pH shifts, rumen, fermentation processes.
Running Title: Microbial Shifts and Rumen pH: Key Factors in Ruminant Nutrition

pH du rumen et changements microbiens : implications pour la nutrition des ruminants – une revue

Résumé

Les écosystèmes microbiens dans le pré-estomac des ruminants, comprenant des bactéries, des protozoaires ciliés, des champignons anaérobies, des bactériophages, des virus et des méthanogènes, jouent un rôle crucial dans la digestion efficace des différents ingrédients alimentaires. Dans cet article de revue, la relation symbiotique complexe entre l'hôte ruminant et les microbes du rumen, mettant en évidence l'impact de la composition du régime alimentaire sur le pH du rumen et la diversité microbienne, a été explorée. Tandis que les pays développés dépendent principalement de l'utilisation de céréales et de concentrés pour améliorer la productivité, cette approche modifie les paramètres du rumen, affectant la répartition des microbes et la santé générale. Le pH du rumen est essentiel pour la stabilité microbienne, les fluctuations influençant la digestibilité des aliments et la santé animale. Les régimes riches en céréales peuvent entraîner une acidose subaiguë du rumen (ASR), affectant les bactéries dégradant les fibres et causant des troubles métaboliques. À l'inverse, les régimes pauvres en fibres peuvent endommager les parois du rumen, affectant la santé animale. Les régimes riches en fibres aident à maintenir des conditions optimales dans le rumen. L'article discute de l'impact sur la santé animale, la production et la qualité du lait/viande, en soulignant la nécessité d'une approche équilibrée dans la nutrition des ruminants. Les stratégies de gestion, telles que les régimes équilibrés, les changements alimentaires progressifs et les ajustements de la fréquence d'alimentation, sont cruciales pour maintenir un environnement sain dans le rumen. Divers additifs et tampons sont utilisés pour stabiliser le pH du rumen. L'étude explore également l'influence de facteurs tels que les graisses alimentaires, les phytochemicals des plantes et les différences individuelles sur la diversité microbienne.

Comprendre l'interaction dynamique entre le pH du rumen et les microbes est essentiel pour optimiser les régimes alimentaires des animaux, minimiser les déchets et garantir une production durable des ruminants. L'étude conclut en soulignant l'importance de prendre en compte l'anatomie intestinale dans les études sur l'écologie microbienne afin d'évaluer de manière complète l'impact de la nutrition sur la santé des ruminants.

Mots-clés *: variations du pH, rumen, processus de fermentation.*
Titre abrégé : Changements microbiens et pH du rumen : facteurs clés de la nutrition des ruminants

Introduction

Ruminant nutrition is a complex discipline that intricately weaves together dietary composition, microbial ecology, and host physiology. At the heart of this complex interplay lies rumen pH, a crucial parameter that significantly influences the microbial community structure and metabolic activities within the rumen. The rumen serves as a fermentation chamber where a diverse array of microorganisms—including bacteria, ciliate protozoa, anaerobic fungi, bacteriophages, viruses, and methanogens —collaborate to break down a diverse array of plants, and chemical-derived ingredients (Lee *et al*., 2011). This process is essential for converting indigestible plant matter into methane, hydrogen, carbon dioxide, and volatile fatty acids (VFAs), which are vital energy sources for ruminants. However, the delicate balance of this microbial ecosystem can be easily disrupted by fluctuations in rumen pH, leading to critical implications for nutrient utilization, animal health, and overall productivity.

The symbiotic alliance between the ruminant host and rumen microbes plays a crucial role in this digestive process (Bath *et al*., 2013; Arjun *et al*., 2023). The ruminant creates an anaerobic environment, facilitating microbial activity, while the rumen microbes reciprocate by generating glucogenic and lipogenic energy sources. This mutualistic relationship not only ensures the breakdown of diverse feed ingredients but also supplies energy, particularly through VFAs, to the ruminant. Additionally, VFAs can serve as an indicator of oestrus in these animals (Ramachandran *et al*., 2020). The harmonious interdependence between the ruminant and its microbial partners contributes to the sustainability of this crucial digestive synergy (Xu *et al*., 2021).

In order to fulfil the global demand for animal protein and enhance the quality of animal products, ruminant nutritionists supplement diets with grains and concentrates, particularly in developed countries, where large proportions of easily fermentable carbohydrates support high milk yields and rapid weight gain in intensive ruminant production systems (Humer and Zebeli, 2017; McGrath *et al*., 2018). This approach has been adopted to some extent in developing countries, involving the use of feed ingredients and crop by-products, such as cassava peel, to improve milk and carcass yields. However, the increased productivity has led to alterations in rumen parameters, including pH and ammonia nitrogen, which in turn is affecting microbial distribution, feed digestibility, and overall health (Plaizier *et al*., 2018; Faniyi *et al*., 2019) of the animal.

Research has shown that optimal rumen pH typically ranges between 6.0 and 7.0, which supports a diverse population of fibre-degrading bacteria essential for effective digestion. When rumen pH falls below this threshold—often due to high-starch diets or rapid fermentation processes—the microbial landscape shifts dramatically. Specifically, populations of cellulolytic bacteria that thrive in neutral pH conditions decline, while lactic acid-producing bacteria proliferate. This shift not only hampers the efficiency of fibre digestion but also increases the risk of metabolic disorders such as ruminal acidosis, characterized by excessive acid production and subsequent drops in pH (Anantasook *et al*., 2013; Cammack *et al*., 2018). Such conditions can lead to decreased feed intake, impaired nutrient absorption, and even severe health issues in ruminants.

Moreover, the repercussions of altered rumen pH extend beyond individual animal health; they also carry significant environmental implications. The fermentation processes occurring within the rumen contribute to greenhouse gas emissions, particularly methane—a potent greenhouse gas that represents a loss of dietary energy (Perez *et al*., 2024). Understanding how rumen pH influences microbial dynamics is therefore crucial not only for enhancing animal performance but also for developing sustainable livestock production practices that mitigate environmental impact.

This review aims to provide a comprehensive synthesis of current research on the relationship between rumen pH and microbial shifts in ruminants, exploring how various dietary strategies—such as forage-to-concentrate ratios, feed additives, and buffering agents—can be employed to maintain optimal rumen pH levels. Additionally, the potential for innovative nutritional interventions to harness beneficial microbial populations while minimizing adverse effects associated with low pH environments will also be explored. By elucidating these connections, this review seeks to contribute valuable insights into optimizing ruminant nutrition, improving animal welfare, and promoting sustainable agricultural practices.

Rumen pH Impact on Bacterial Dynamics: Implications for Ruminant Nutrition

Diet composition significantly affects bacterial populations in the rumen, with notable changes occurring during weaning and dietary transitions (Meale *et al*., 2016; Ramos *et al*., 2021). These changes aim to improve feed efficiency, animal productivity, and reduce the environmental footprint of ruminants. The relationship between diets, rumen pH, and rumen microbes is intricate, with each factor influencing the others. Understanding and evaluating this relationship at the molecular level, considering phylum, genus, and individual microbial levels, provide a more holistic approach to describing microbial communities and their functions under different feeding and environmental conditions (Morgavi *et al*., 2013; Moraïs and Mizrahi, 2019). Molecular-based assessments are essential for a comprehensive understanding, as culture-based methods may underestimate microbial diversity and functions. Overall, the state and pattern of this tripartite relationship have significant implications for animal productivity, feed digestibility, animal health, and the environmental impact of ruminants.
The pH of the rumen is an important factor that controls a number of important digestive functions in ruminants (Dijkstra *et al*., 2012; Nagaraja, 2016). For optimal functions, a pH range of 6-7 is acceptable for ruminants, however, this is subject to several conditions like type and composition of diet, frequency of feeding and level of salivation (Sharma *et* al., 2018; Reddy and Hyder, 2023). A healthy and balanced rumen environment is important as it determines the microbial type and population present in the rumen (Krause *et al*., 2013; Faniyi *et al*., 2019). These microorganisms especially the ones responsible for digestion of fibre are of great importance to ruminants. An increase or decrease in rumen pH will cause a decline between fibre-digesting microorganisms and the others present in the rumen. Fibre is important to ruminants because it provides additional energy especially among dairy animals for milk production and volatile fatty acids for milk fat, and also promotes healthy rumen balance in terms of pH and microbial population. Decrease in rumen pH which is usually associated with consumption of highly fermentable carbohydrates (usually grains), decrease in fibre intake and general decrease in feed intake can be detrimental to the health and productivity of ruminants. Fluctuations in fermentation process, milk production and general health can be asymptomatic of decreased rumen pH. Increased ruminal pH will also reduce microbial efficiency (Hungate, 1966; Russell and Rychlik, 2001), impair fibre digestion (Mertens, 1997), increases ammonia accumulation (Leng, 1990); Alter absorption and motility in the rumen (Allen, 1997); lower acid production (Dijkstra *et al*., 2005), thus creating a potential risk of metabolic disorders (Owens *et al*., 1998), and ultimately impairing animal performance and health (Reddy and Hyder, 2023). Hence, maintaining an optimum pH in the rumen cannot be overemphasized.

Impact of Diet Composition on Ruminant Health: Insights into Acidosis and fibre Requirements

Diet composition plays a pivotal role in determining the health, productivity, and welfare of ruminant livestock. As herbivores with complex digestive systems, ruminants rely on a diverse array of dietary components to meet their nutritional needs and maintain optimal physiological functions. Among the various factors influencing ruminant health, the balance and quality of dietary ingredients, particularly the levels of fermentable carbohydrates and fibre, emerge as critical determinants with profound implications for rumen health and overall well-being.

Central to the discussion of diet composition and its impact on ruminant health is the phenomenon of sub-acute ruminal acidosis (SARA), a metabolic disorder characterized by excessive fermentation of readily fermentable carbohydrates in the rumen. High-grain diets, commonly used in ruminant production to expedite weight gain in beef cattle and enhance milk production in dairy cows, predispose animals to SARA due to their elevated levels of starch and sugars (Zebeli & Metzler-Zebeli, 2012; Ferguson, 2018; Plaizier *et al.*, 2018). This rapid fermentation leads to the accumulation of lactic acid and volatile fatty acids (VFAs), consequently lowering the pH levels in the rumen and creating an acidic environment detrimental to ruminal microbial populations and digestive processes.

Understanding the intricacies of SARA is imperative for mitigating its negative impacts on ruminant health and productivity. While the exact threshold for diagnosing SARA remains subject to debate, prolonged periods of ruminal pH below the optimal range of 6.0 to 6.2 are associated with subclinical acidosis (Enemark *et al.*, 2004), compromising rumen function and nutrient utilization. Clinical manifestations of SARA encompass a spectrum of physiological disturbances, including reduced feed intake, altered microbial populations, impaired nutrient absorption, and systemic inflammatory responses, culminating in diminished production performance and increased susceptibility to secondary health disorders (Plaizier *et al*., 2018; Antanaitis *et al*., 2024)

In addition to the challenges posed by high-grain diets and SARA, the importance of dietary fibre in maintaining rumen health cannot be overstated. fibre serves as a crucial substrate for rumen microbial fermentation, promoting rumination, saliva production, and buffering capacity, all of which are essential for stabilizing ruminal pH and sustaining microbial populations (Weimer, 1998). However, the quality and quantity of dietary fibre vary widely among feedstuffs, necessitating careful consideration of fibre sources and particle size to optimize rumen function and nutrient utilization. Some of the insights are stated below:

High Grain Diets and Sub-Acute Ruminal Acidosis (SARA): The use of cereals/grains in ruminant production is a widely accepted feeding strategy to fatten ruminants (beef) under a short period of time and increase milk production (dairy) (Oetzel, 2007; Kmicikewycz, 2014). However, this strategy is plagued with a digestive disorder arising from high fermentation in the rumen environment, subsequently leading to the build-up of lactic acid and volatile fatty acids which lowers the pH levels in the rumen (acidosis) (Oetzel, 2007; Krause and Oetzel, 2006; Krause, 2008; Kmicikewycz, 2014; Bipin *et al.*, 2016). An acidic rumen environment can negatively impede on fibre-digesting bacteria population in favour of acid-tolerant bacteria. SARA has been reported to have negative impacts on both health of animals and profitability of herds especially in dairy herds under optimum management (Enemark, 2008; Kitkas *et al*., 2013; Kleen *et al*., 2013; Plaizier *et al*., 2014; Antanaitis *et al.*, 2015). Although the pH levels for SARA is widely debated among studies, Li *et al*. (2013) opined that a pH range of 5.2 to 6.0 over a prolonged time frame effectively captures conditions for SARA. Krause and Oetzel (2006) also indicated daily reduction in ruminal pH as a typical characteristic of SARA which occurs over a few hours daily as buttressed by Plaizier *et al*. (2014). However, Keunen *et al*. (2002) reiterates that taking a measurement of rumen pH is the only accurate and reliable means of diagnosing SARA in ruminants.

Dong *et al*., (2013) in a study documented pH levels lower than 5.8 which persisted for over 3 hours after feeding high concentrate diets to lactating goats. Likewise, the research documented systemic inflammatory response to SARA in goats as is similar in other documentation which were adjudged to the accumulation of lipopolysaccharides in the circulatory system of dairy cows (Plaizier *et al*., 2005; Emmanuel *et al*., 2008; Khafipour *et al*., 2009a). Clinical signs of SARA are not particular in dairy cows as opined by several authors however, organ and tissue inflammation are said to be a major characteristic, resulting in reduced feed intake, decrease in feed digestibility, reduction in milk yield and milk fat composition, liver abscesses and possible lameness (Krause and Oetzel, 2006; Radostits *et al*., 2007; Plaizier *et al*., 2008). Abdela (2016) reiterated that injured gastrointestinal lining accompanied by specific or systemic inflammation often facilitate a lot of these negative effects associated with SARA. A few studies have been geared towards preventing SARA in ruminants some of which includes the use of sodium bicarbonate and monensin (Paton *et al*., 2006) although these methods have been less than optimal in consistently maintaining rumen pH values.

Low fibre Diets: The importance of fibre in the diets of ruminants cannot be overemphasized as it is just as important as protein and energy which is usually the major focus of most nutritional programs. As fibre cannot be digested by gastrointestinal enzymes present in mammals but by microorganisms particularly found in the rumen environment, it is imperative to ruminant diets. Its' importance in stimulating digestibility, increasing feed intake and salivation during regurgitation/rumination (cud chewing) which is a necessary process for lowering rumen pH (buffering) has been well documented (Duan *et al*., 2021). However, fibre constituents vary in all ruminant feed stuff which can lead to feeding diets low in fibre content without forehand information. This can result in damage to the walls of the rumen, which can be permanent over an elongated period. Pitt and Pell (1997) postulated that diets with neutral detergent fibre (NDF) content of up to 34% are necessary to maintain a steady state of the rumen environment especially during periods of reduced feeding frequency, which points to the importance of fibre and its specific constituents in maintaining the stability of the rumen. Likewise, the size of the fibre fed to ruminants is a major determinant of its efficiency. Too large particle size forms the mat material present in rumen which is important for optimal ruminal function and nutrient digestion, while finely chopped particles may fall short of promoting rumen health.

Fibre-Rich Diets: Diets adequate in fibre content is important to maintain optimal rumen environment for nutrient digestion, increased feed intake and balance the microorganism population that is responsible for a whole lot of biochemical and metabolic functions. Diets rich in fibre helps to promote cud chewing (rumination) and salivation, subsequently increasing and/or maintaining rumen pH (Salfer *et al*., 2018). In cases of ruminal acidosis like SARA, incorporating fibre-rich components into grain diets can greatly help to bring back the acidic rumen environment to optimum levels. However, care must be taken in feeding fibre diets to ruminants as the fibre fractions; acid detergent fibre (ADF) and neutral detergent fibre (NDF) has been documented to be negatively correlated with feed intake. Thus, feeding diets with higher levels of NDF and ADF can result in lower feed intake which would be counterproductive.

Rumen health impact on ruminant productivity: Insights into nutrition and metabolic disorders

The health of the rumen significantly influences the productivity of ruminant animals. This state the crucial relationship between rumen health, nutrition, and metabolic disorders in determining overall productivity. Understanding these dynamics is essential for optimizing ruminant nutrition and mitigating metabolic challenges in livestock management. The general state of the rumen can greatly affect the health and productivity of ruminants as it is responsible for the additional energy and nutrients for optimal performance and production.

***Digestive Efficiency*:** optimal pH of the rumen guarantees balanced microbial population in the especially fibre-digesting bacteria which contributes to the production of volatile fatty acids and the synthesis of various vitamins and minerals, all of which is needed and necessary for energy production, improved health and milk synthesis in case of dairy animals. Li (2017) and Paz *et al*. (2018) have documented the correlation between microbes in the rumen and feed efficiency in dairy cows. In addition, Shabat *et al*. (2016) reported specialised rumen microbes being able to sustain the hosts' energy requirements under certain conditions. The report went on to indicate that animal feed efficiency phenotype can be accurately predicted by analysing the genes and species of microbes present in the rumen. However, a study by Liu *et al*. (2019) documented that some bacteria hindered the digestibility of neutral detergent fibre in goats.

Nutrient Utilisation: Discrepancies or shifts in ruminal microbial population can result in reductions in nutrient uptake and hence utilisation. pH shifts which favour the methanogenic microbe population often leads to loss of energy from feed stuff during the production of methane. Likewise, accumulation of VFAs due to the reduction of cellulolytic microbes in the rumen results in the nutrient loss during digestion and uptake, while the nutrients absorbed is directed towards alleviating stress conditions imposed by unfavourable rumen environments and metabolic disorders like SARA. The fermentation process aided by rumen microbes provides VFAs and vitamins through the degradation of fibres and roughages, and other organic matters in the diet. Furthermore, the synergistic relationship between rumen microbes and the epithelial cell metabolism of the intestines impacts on general health of the animal(s), nutrient utilisation and immune functions (Liu *et al*., 2017).

Metabolic Disorders in ruminants: these are a form of economic loss to farmers which a continuous or sharp decrease in rumen pH is one of the causes. With symptomatic conditions like stress and discomfort, reduction in feed intake which are resultants of disorders like sub-acute or acute ruminal acidosis which renders ruminants unproductive in dire cases.

A study by Kofler *et al*. (2023) revealed a significant increase in lameness of first-lactation cows subjected to severe SARA conditions and compared cows subjected to the light and moderate SARA conditions. Lameness in dairy production significantly affects animal welfare indices as well as production performance (Machado *et al*., 2010; Gundelach *et al*., 2013; Fuerst-Waltl *et al*., 2021). Other studies on SARA have revealed a correlation between SARA and ischemia, circulatory disturbances and ischemia (Ossent and Lischer, 1998; Greenough 2007; Danscher *et al*., 2010). These studies reiterated the effect of metabolic disorders (SARA) on the welfare and productivity of animals.

Milk and Meat Quality: Milk quality is largely dependent on the conditions of the rumen, since dairy animals get the extra energy, volatile fatty acids and other necessary components of milk and milk production from the digestion process which occurs in the rumen. Research conducted by Fairfield *et al*., (2007) indicated that deliberately inducing subacute ruminal acidosis (SARA) resulted in a reduction in milk fat percentage while simultaneously increasing milk protein content.

Other studies suggested that short term SARA did not impact on milk fat or protein contents (Khafipour *et al*., 2009b; Li *et al*., 2012). Another study by Dong *et al*. (2013) reported changes in fat and protein content of milk from animals fed high concentrate diets. These changes in fat and protein composition negatively impaired on the quality of milk produced. This decline in quality was associated with acute phase and inflammatory response to the fed diets which resulted in energy redistribution in the liver. Likewise, plasma serum levels like glucose and leptin increased which could significantly affect quality of meat derived from such animals. It was concluded that feeding a high-concentrate diet to lactating goats over a prolonged time will result in the decline of milk protein and fat composition. Dancsher *et al*. (2015) in a study reported a 4.14% decrease in milk fat from SARA induced animals compared to the control group. Other authors (Xu *et al*., 2016; Bipin *et al*., 2016; Malekkhahi *et al*., 2016) all reported declines in milk fat content during SARA. Contrastingly, Oetzel (2005), Enjalbert *et al*. (2008) and Tajik *et al*. (2009) all reported no reduction in milk fat content during experimentally induced SARA. However, these differences have been attributed to difference in herd size (as it is opined by Kleen *et al*. (2003) that milk fat decrease is undetectable in bulk tank testing) and duration of exposure to SARA (as opined by Krause and Oetzel (2005) and Oetzel (2005) that short-term SARA disruptions have no significant impact on milk contents).

Impact of dietary fat and phytochemicals on rumen microbial populations: Antiprotozoal effects

Dietary fat:

In the study of Abubakr *et al.* (2012) which involved the use of dietary fat (palm kernel cake, decanter cake diet and control diet +5% palm oil), there was reduction in the microbial population of protozoa. The diets which reduced the protozoa population contained C-12:0 and C-14:0 which are medium chain fatty acid while the control had no C-12:0 and C-14:0. It could be deduced that medium chain fatty acids were toxic to rumen protozoa. Although the palm kernel cake diet contained higher C-12:0 and C-14:0 (53.41 and

16.21g/100g) of fatty acid than other palm product used which had 0.02 and 0.05g/100g of C-12:0 and C-14:0 for decanter cake, and 0.01 and 0.81g/100g of C-12:0 and C-14:0 for control diet +5% palm oil, they still elicited the same effect on the protozoa and reducing it to same (2.1 x 10^5) compared to the control (6.2 x 10^5). This reduction could also not be attributed to pH because all the animals fed dietary source had the same number of protozoa. All the fat sources contained C-12:0 and C-14:0 medium chain which was not present in the control diet. It could be deduced that medium chain fatty acids were toxic to rumen protozoa. Although the diet contained varying level of the C-12:0 and C-14:0 fatty acid, they still elicited the same effect on the protozoa. It can be inferred that even a small presence of C-12:0 and C-14:0 has an antiprotozoal effect. The reduction in protozoa population is expected to enhance fibre digestion by promoting increased bacterial, particularly cellulolytic, biomass. This effect is attributed to the decreased engulfment of bacteria by protozoa (Abubakr *et al*., 2012).

Phytochemical:

The necessity to find plant alternatives arose from the European Union's ban on the use of antibiotic growth promoters, which forced rumen ecologists to hunt for other sources capable of producing performance similar to that of an ionophores (Michalak *et al*., 2021). There are plants that possess secondary metabolites with antibacterial qualities. As an illustration, the secondary metabolites of neem (Akihisa *et al*., 2021), ginger (Setyawati *et al*., 2021), cinnamon (Vasconcelos *et al*., 2018), garlic (Sut *et al*., 2020), etc.; such as tannin, saponin, azadirachtin, allicin, diallyl disulphide, etc., have antibacterial, antifungal, and antiprotozoal qualities. These plants influence both gram-positive and gram-negative bacteria due to their antibacterial properties. However, because gram-negative bacteria have peptidoglycan in their cell walls, which prevents the easy entry of certain biochemical compounds (Tavares *et al*., 2020), gram-positive bacteria are more affected than gram- negative bacteria. As a result, when these plants are fed to animals, the gram-positive microbial population tends to diminish and the gram-negative microbial population grows, as seen by the drop in the acetate to propionate ratio. Moreover, tannins work best against germs that break down fibre. According to McSweeney *et al*. (1999), animals given tannin-rich *Calliandra calothyrsus* showed a significant decrease in the populations of Ruminococcus and Fibrobacter species, but this diet had less of an impact on fungi, protozoa, and proteolytic bacteria. According to Sotohy *et al*., (1997), goats fed a tannin-rich plant (*Acacia nilotica*) had a considerable decrease in the overall number of bacteria in their rumen, with the amount of this feed in the diet directly correlated with the decrease in numbers. On the other hand, ruminants that consistently consume diets high in tannins typically cultivate a microbiota that is resistant to elevated tannin levels (Kamra, 2005). For example, the high tannin content of Acacia and *Calliandra calothyrsus* that the feral goats and camels eat allows them to tolerate tannins in their diet because they have a high concentration of bacteria that are resistant to tannins, such as *Selenomonas ruminantium* and *Streptococcus caprinus*. The microbial community's adaptability has caused a change in growth towards bacteria that are resistant to tannin. Additionally, the microbe that predominates in the rumen at a given time may depend on the type of diet provided to the animal. In one investigation, only eight bacteria were cultivated from the sorghum top fed to the animal (Isah *et al*., 2015). The decreased pH could result from some sorghum grains that were picked along with the sorghum top. There were nine to thirteen microbial cultures from the other treatments that were given forages of varying quality.

The total number of bacteria and fungi were decreased, and the population of protozoa rose in the animal given sorghum tops. Even though the animal given sorghum had the lowest pH, pH cannot be the only factor in this (Isah *et al*., 2015). Another aspect might be the thick cell wall of the sorghum top, which makes it harder for the easily degradable organic materials found in other supplemented diets to break down. Secondly, the secondary metabolite found in the sorghum top may also be responsible, as it may have an antibacterial effect on the microorganisms.

Rumen pH Dynamics: Implications on Microbial Ecosystem, Composition and Animal Health

Rumen pH plays a central role in influencing microbial populations and ruminant productivity (Nagaraja, 2016; Faniyi *et al*., 2019). Changes in pH impact ruminal microbial activities, enzyme requirements for feed degradation, and fermentation product concentrations. For example, during oestrus, bovines exhibit increased concentrations of acetate, propionate acid, and 1-iodoundecane in urine and faces, providing insights into reproductive status. This knowledge has been utilized to develop a pheromone sensor for enhancing reproductive efficiency in animals experiencing silent oestrus, underscoring the importance of proper feeding and physiological balance in the foregut (Wiegerinck *et al*., 2011). The stability of rumen microbial ecosystem is essential, but it is subject to significant changes, especially in pH levels influenced by diet. Rumen microorganisms are sensitive to pH variations, making the maintenance of optimal pH crucial for the stability and persistence of the rumen microbes (Owens and Basalan, 2016). The removal of fermentation end products, particularly volatile fatty acids (VFAs), is essential for stability, as prolonged depression of pH can be inhibitory to microbial communities.

Maintaining an optimal pH range through appropriate feeding and management practices is essential and while being cautious of the implications of these diets on total animal welfare, an understanding of the dynamic of rumen micro-organisms and how they are affected by rumen pH will go a long way to influence how diets are constructed and what kinds of ingredients to utilize. An appropriate comprehension of the interaction between rumen pH and bacteria may even aid in optimizing the amount of ingredient used in formulations to minimize waste due to impaired digestion brought on by disruption of rumen microbes. A core set of micro-organisms exist in the rumen at the phylum level regardless of the type of diet provided to animals; nevertheless, food and rumen pH affect changes in the microbial community at the individual level. While bacteroidetes are more common in diets high in hay, firmicutes are likely to be more prevalent in diets heavy in grain (Pitta *et al*, 2010; Wang *et al.,* 2017). However, both can occasionally have a relative abundance of 80% or more. Firmicutes and bacteroidetes are relatively abundant, with a presence rate of more than 80%. Other microorganisms that fluctuate depending on diet include actinobacteria, proteobacteria, and fibrobacteres, which increase with higher fibre. Prevotella, ruminococcus, butyrivibrio, syntrophococcus, fibrobacter, and bacteroides are common genera of bacteria (Neubauer *et al*., 2018; Zeineldin *et al*., 2018).

The decrease in cellulolytic germs, such as *Fibrobacter succinogens*, indicates that gram-negative bacteria can withstand a certain pH level before they start to lyse or die (Saluzzi, 1993; Elmhadi *et al*., 2022). As a result, gram-negative bacteria that proliferate excessively or decline irrationally produce more endotoxins, which can be hazardous to the host animals. The presence of lipopolysaccharide (LPS) serves as a marker for the death of gram-negative bacteria. Prolonged low pH, on the other hand, compromises the ruminant's gut integrity, creating space for secondary infections that pose a risk to the animal's health (as seen by diarrhoea and lameness) and ultimately result in financial loss due to decreased animal productivity. Low pH anatomically damages the ruminant foregut and hindgut by degrading the villi and causing structural alterations in the intestine.

Microbiologically, diet and pH cause shift in the rumen, colon and caeca to influence concentration of endotoxin in the gut. Ensuring the well-being of the hindgut is paramount for ruminant ecologists and nutritionists, particularly given the substantial contribution of volatile fatty acids (VFAs) from hindgut fermentation to the overall nutrition of ruminants (Faniyi *et al*., 2019; González-Ortiz *et al*., 2019). Consequently, prioritizing hindgut health should be of primary concern. Some microbes have ability to thrive on any diet, be it high grain or high concentrate diet, e.g. *prevotella* spp, making them extremely versatile microbes. Besides diet and pH, individual animal also determines the type and population of microbes that would be in their gut even when fed the same diet quality and quantity, which may be caused by difference in their genetic potential (Benson *et al*., 2010; Roehe *et al*., 2016). Due to the short and few gut villi, low pH anatomically compromises the ruminant's foregut and hindgut by eroding the villi and causing structural changes in the gut physiology. This may be the cause of the accumulation of VFA on the rumen under rapidly fermentable starch.

According to the numerous studies that have been reviewed, adding grain or starch to the diet may not be a terrible idea for ruminant production; in fact, it may even promote the growth of cellulolytic microorganisms more effectively than using grain or very high fibre alone. Therefore, as long as the percentage of fermentable starch in the diet does not exceed 35%, fibrobacteres can grow and thrive. Moreover, the starch will provide fibrolytic micro-organisms the energy they need to proliferate. Therefore, diets containing less than 35% fermentable starch are not harmful to the proliferation of fibrobacteria. Ruminant production should critically assess the impact of diet on pH, rumen microorganisms, and climate since the idea of animal production has evolved from the mere provision of animal products to include the effect of animal production on land, water, and climate and how it impacts the gastrointestinal tract, animal welfare, and animal health. Since there is a dearth of data on the impact of nutrition on gut anatomy, microbial ecology studies should take into account the histology, morphology, and structure of the rumen gut.

Optimizing Ruminant Productivity: Strategies For Effective Management

Management is a very important aspect of animal husbandry without which productivity cannot be maintained. This art has led to development of various strategies and approaches to optimise production in all branches of livestock production. Its' importance in ruminant production cannot be overemphasised especially in maintaining a healthy rumen environment. Over the years, a number of strategies have been developed especially on diet and feeding to help ruminants maintain optimal rumen conditions especially in the modern phase of intensified and increased production to meet the ever-increasing global demands.

Some of these approaches that need more scrupulous and well-grounded research work comprise of:

Balanced Diet: like in monogastric animals, ensuring that fed diets have a proper balance of necessary components necessary for maintaining optimal rumen condition is one of the simplest means of optimising performance and production. Balanced proportion of roughages (fibres) and concentrate feeds helps to ensure the maintenance of a healthy and stable rumen environment in terms of pH and microbial shift. Diets rich in roughage can increase chewing, secretion of saliva which in turn acts as an alkaline buffer in the rumen. Diets rich in highly digestible fibre and little starch content is more advantageous to maintain rumen pH, feed intake and digestibility (Parish, 2007).

Gradual Diet Changes: a gentle transition of ruminant livestock to new diets over a period of time is very beneficial to animals. This allows time for the rumen microbe population to gradually adjust to the new diet without imposing any metabolic stress or disorder on the animals. Likewise, changes on the performance and/or productivity of the animals can be accessed, and necessary adjustments made. This approach is particularly popular during experimental research as it helps to eliminates errors from sudden introduction of new diets to ruminants. The adjusted rumen microbial population in such experiments tend to produce more accurate data for the research. In addition, Kaufman *et al*. (1976) concluded that feeding high concentrate diets within short time frames can result in ruminal acidosis as well as other metabolic disorders.

***Fibre Content*:** it is important to feed diets rich in fibre to ruminants in order to help maintain their rumen environment. However, it is important to note that the fibre content of the diet must be at optimal levels and be of benefit to the animals. Research have shown that NDF and ADF fibre fractions have a negative correlation to feed intake (Allen *et al*., 2019), likewise, particle size of the fibres is important for proper rumen function and digestion of nutrient of nutrient (Parish, 2007). Furthermore, high levels of effective fibre in diets increases frequency of salivation and rumination (Salfer *et al*., 2018), thus necessary for maintaining rumen pH and feed intake (Parish, 2007).

***Feeding Frequency*:** a popular opinion is that manipulation of feeding strategy is carried out to stabilize diurnal fluctuations in ruminal fermentation patterns (Nocek, 1992). This stability is also postulated to enhance digestibility of fed fibre, maintain the production of microbial end products and maximise microbial yield. Gibson (1984) and Nocek (1987) in their researches documented improved milk fat percentage of up to 7% in dairy cows fed between four to six times daily compared to those fed only twice. This observation affirms the idea that increased frequency of feeding leads to reduced diurnal fluctuations in ruminal pH, consequently increasing cellulolytic bacterial activity and acetate concentration in relation with increase in milk fat percentage (Nocek, 1987).

Yang and Varga (1989) also opined that increasing feeding time per day might decrease acidosis by reducing starch intake per meal, possibly resulting in a more stable rumen environment. Soto-Navarro *et al*. (2000) in another study on feeding frequency and fluctuations documented that increase in feeding frequency appears to stabilise the rumen environment. Although, reduced VFA concentrations and increased acetate to propanoate ratio with possible lower efficiency in energy utilisation by limit-fed cattle was observed in animals fed twice daily as well as those fed once daily. (Soto-Navarro *et al*., 2000).

***Buffers and Additives*:** Farmers and producers have also relied on the use of additives and buffers to help stabilise rumen pH especially during periods of dietary challenge. Although saliva is a natural buffer for ruminants, other substances and organisms has been documented to be or benefit in maintaining rumen pH. Probiotics like yeast (*Saccharomyces cerevisiae*) has been documented to be of benefit in stabilising rumen pH and dry matter digestibility (Cagle *et al*., 2018). Several studies (Stella *et al*., 2007; Moallem *et al*., 2009) on live *Saccharomyces cerevisiae* has documented increased feed intake, feed efficiency, improved milk production and stress alleviation in lactating dairy cows which are indications of a stable rumen pH and environment. Zhang *et al*. (2022) in another study documented that yeast supplementation favoured a steady rumen pH consequently improving nutritional of beef cattle. Other documented buffers and additives include sodium bicarbonate and monensin (Mutsvangwa *et al*., 2002; Paton *et al*., 2006). In a separate study, Guo *et al*. (2013) recorded the favourable impact of incorporating pelletized beet pulp as a feed additive. This inclusion was found to mitigate the risk of subacute ruminal acidosis (SARA), enhance fibre digestion, and elevate antioxidant status in dairy cows. Table 1 shows a summary of some key works on rumen pH and how it affects microbial activities in the rumen of animals.

Conclusion

A thorough understanding of the intricate interplay between diet, rumen pH, and microbial populations is imperative for enhancing ruminant health and productivity. Thus, more research on integrating nutritional management practices that prioritize rumen health and microbial ecology is essential for promoting sustainable livestock production and ensuring animal welfare.

Conflict of interest

The authors declare no conflict of interest.

Table 1: Rumen pH and Microbial Shift and implications for Ruminant Nutrition

Focus of Study	Inferences	Author
Change in diet	Providing high-concentrate diets over brief periods can lead to ruminal acidosis and various metabolic issues.	Kauffman *et al.* (1976) Hua *et al*. (2017) Ogata *et al*. (2019)
Fibre particle size	Diets with abundant effective fibre elevate salivation and rumination frequency, essential for preserving rumen pH and promoting feed intake.	Parish (2007) Salfer *et al*. (2018) Jiyana *et al.* (2021)
Feeding frequency	Raising the frequency of feeding stabilizes the rumen environment, but it may lead to decreased efficiency in energy utilization by limit-fed cattle. Both twice-daily and once-daily feeding resulted in reduced volatile fatty acid concentrations and an increased acetate to propionate ratio.	Soto-Navarro *et al*. (2000) Sun *et al*. (2019) Saldana *et al*. (2021)

Feeding frequency	Expanding the daily feeding duration could mitigate acidosis by lowering starch intake per meal, potentially leading to a more consistent rumen environment.	Yang and Varga (1989) Hernández *et al*. (2014)
Buffer and additives (yeast)	Enhanced feed intake and efficiency, along with improved milk production and stress relief in lactating dairy cows, signify a stable rumen pH and environment. This steady rumen pH, in turn, contributes to better nutritional and physiological conditions in beef cattle.	Stella *et al*. (2007) Maollem *et al.* (2009)
Buffer and additives (beet pulp)	Boosting fibre digestion and enhancing antioxidant status in dairy cows.	Guo *et al.* (2013) Mohsen *et al*. (2021) Habeeb (2024)
Buffer and additives (sodium bicarbonate)	Decreased duration of ruminal acidosis may minimize its adverse impact on feed digestion.	Paton *et al*. (2006) Laskoski *et al*. (2014) Jaramillo-López *et al.* (2017)

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