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Review article

Preventing ruminal acidosis and optimizing ruminant performance by carbonate buffer supplementation: A review

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Abstract

Feeding high-concentrate diet is an effective way of improving the performance and feed efficiency of ruminants. However, feeding high-concentrate diet to ruminants may lead to subacute ruminal acidosis (SARA) incidence. This study aims to determine the effect of giving carbonate compounds to ruminants on high-concentrate feed. Carbonate compounds often function as a buffer to maintain rumen pH and prevent the occurrence of SARA. Several studies have shown that SARA can cause rumenitis, milk fat depression, laminitis, liver abscess, and death. Carbonate compounds can be given in single form or in combination with other compounds such as sodium (Na+), calcium (Ca^{2+}), potassium (K^{+}), and magnesium (Mg^{2+}). This combination often leads to the formation of complex compounds, such as sodium bicarbonate ($NaHCO_3$), calcium carbonate ($CaCO_3$), sodium carbonate (Na_2CO_3), and potassium carbonate (K_2CO_3). $NaHCO_3$ has been reported to be one of the most popular carbonate compounds to prevent and reduce SARA. Consistent findings across several investigations indicate that supplementation of carbonate buffer at a level of 0.7%–1.5% plays a role in stabilizing ruminal pH, reducing the risk of SARA, and supporting efficient fermentation.

Keywords: Acidosis, Carbonate compound, High-concentrate diet, Rumen pH, Ruminants

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INTRODUCTION

Currently, the growing market demand for meat and milk is driving livestock businesses to increase production. To obtain high-quality products and assure consumer safety, animal welfare–oriented agricultural practices are required, particularly in intensive farming systems. One common strategy used in this system is to provide a high-concentrate, low-forage diet to improve feed efficiency and ruminant performance (Golder and Lean, 2024). However, this feeding strategy disrupts the rumen digestive process (Wang et al., 2023; Wang et al., 2024). This disruption can result in rumen acidosis, a metabolic disorder common in intensively raised cattle. Subacute ruminal acidosis (SARA) is the most common form of this condition.

SARA is a metabolic disorder characterized by a gradual decrease in rumen pH to below 5.6 in a few hours each day (Plaizier et al., 2008; Elmhadi et al., 2022). This phenomenon is relatively common, with a reported prevalence of 19-26% in dairy cattle and 23% in beef cattle in intensive systems (Owens et al., 1998; Penner et al., 2007; Plaizier et al., 2008). This digestive disorder often occurs in cattle fed high-concentrate diets containing high levels of non-fiber carbohydrates (NFCs) (Elmhadi et al., 2022). The high content of rapidly digestible carbohydrates in the concentrate increases microbial digestive activity, thereby increasing volatile fatty acids (VFA) production. However, the high VFA production is not balanced by buffer production, leading to VFA accumulation and lactic acid synthesis, resulting in decreased pH (Hernández et al., 2014). This condition often does not show obvious clinical symptoms, but it has serious consequences for livestock health and productivity. SARA can cause various complications such as rumenitis, decreased milk fat content, laminitis, liver abscesses, and in severe cases, lead to livestock death (Hernández et al., 2014; Malafaia et al., 2022).

The Addition of buffers to maintain rumen pH stability is one approach to avoid acidosis. Using a feed buffer may increase rumen pH during high VFA production and provide a more favorable environment for microbial activity (Ramos et al., 2022). $NaHCO_3$ (Mao et al., 2017), magnesium oxide (MgO), and $CaCO_3$ (Neiderfer et al., 2020) are often used as ruminal buffers. Russell and Chow (1993) reported that Na_2CO_3 has been utilized since the 1960s to regulate pH levels in the rumen of animals fed a high-concentrate diet. Supplementing a high-concentrate diet with $NaHCO_3$ promotes ruminal fermentation by elevating rumen pH and decreasing the amounts of lactate and biogenic amines (Mao et al., 2017). The pyrosequencing study revealed that SARA-induced diet disrupted rumen fermentation and decreased rumen microbial diversity (Mao et al., 2013), and feeding $NaHCO_3$ could aid such detrimental effect by enhancing microbial diversity index and reducing bioamine production (Mao et al., 2017).

In the present review, we revisit the roles of the inclusion of carbonate buffers and their mode of action in maintaining rumen metabolism by regulating rumen microbial ecology. Our goals are to interpret the updated scientific literature to offer context for describing the action buffers for regulating rumen pH a consideration for use alone or in combination by researchers and cattle nutrition advisors.

RUMINAL ACIDOSIS IN RUMINANTS

The maintenance of the reticulorumen's health is critical for the productivity and health of ruminants (Van Vuuren et al., 2012; Alves, 2024). The reticulorumen pH of cattle, particularly dairy cows, is an important indicator to evaluate the efficiency of rumen fermentation and the susceptibility to gastrointestinal disorders (Neubauer et al. 2018). Feeding more grains and less fiber, as well as reducing forage particle size, all reduce the time spent chewing (Yang and Beauchemin 2006; Fairfield et al. 2007; Hernández et al., 2014). Several studies have shown that saliva production is affected by the length of time spent chewing, eating, and

rumination. Giger-Reverdin et al. (2014) suggested that as the chewing rate per kg of dry matter increased, the saliva production increased. Inorganic buffers in saliva, such as $NaHCO_3$, also aid in counteracting the organic acids produced by rumen fermentation (Plaizier et al., 2008). To keep the acid-base balance in the rumen, acid is produced, saliva must neutralize it, and the ruminal epithelium must absorb the products of fermentation (González et al., 2012). In addition, management factors, including stressors, inadequate nutrition (including feed changes), and interruptions to regular feed consumption routines, may cause ruminal acidosis (Hernández et al., 2014).

According to previous studies, there are two main groups of ruminal acidosis. They are summarized in Figure 1. Two clinical forms of ruminal acidosis are acute ruminal acidosis (ARA) and SARA (Hernández et al., 2014). This classification is based on the decrease in rumen pH (Aschenbach et al., 2011). According to Hernandez et al. (2014), acute ruminal acidosis is a metabolic condition characterized by a decrease in blood pH and bicarbonate levels. When the ruminal pH falls below 5.0, animals experience depression, decreased ruminating, appetite loss, diarrhoea, and dehydration. In addition, microbial metabolism and feed digestion are altered, inflammatory processes occur, and milk lipid levels decrease (Dijkstra et al., 2012). Despite the fact that SARA is a condition in which rumen fermentation patterns are momentarily disrupted, the intensity and duration are insufficient to produce clinical symptoms promptly (Nocek, 1997; Maulfair et al., 2013).

SARA is considerably more prevalent than ARA in modern ruminant production systems. The prevalence of SARA has been reported to range between 11%-26%, with rates of 11%-20% during early lactation and 18%-26% during mid-lactation (Kitkas et al., 2013; Atkinson, 2014; Stefańska et al., 2016). A farm with a known history of high incidence exhibited even greater prevalence, reaching 48.2%, 53.8%, and 65.3% at 30, 90, and 150 days in milk (DIM), respectively (Kitkas et al., 2019). The condition is a common metabolic disorder that occurs in livestock species, including cattle, sheep, and goats, that receive high-grain intensive feeding practices (Huo et al. 2014; Wang et al., 2024). Gozho et al. (2005) reported that SARA was indicated by a continuous decrease in rumen pH below pH 5.6 for more than 3 hours every day. Other study defined SARA as a condition of ruminal pH decline from 5.5 to 5.0 for 111 to 180 minutes every 24 hours (Jaramillo-López et al., 2017). This condition can lead to considerable financial losses for dairy herds and is characterized by a reduction in dry matter intake, milk production, and profitability. It also causes an increase in the number of animals that are culled or lost due to mortality (Plaizier et al., 2008; Elmhadi et al., 2022).

Rumen buffering from saliva is unable to prevent the accumulation of organic acids in the rumen, such as VFA and lactic acid, thus leading to a rumen pH drop. Feeding more grains and less forages promotes the accumulation of VFA in the rumen (Baffa et al., 2024), since grains are more rapidly digested in the rumen than forages (Hu et al., 2007; Aschenbach et al., 2011). SARA can also affect dairy cows that are fed on pasture. According to a study from Ireland (O'Grady et al., 2008), highly digestibility forages in pasture may be the cause of SARA.

The initial occurrence of SARA can be associated with rumen environment disturbance. Common clinical signs include diarrhoea, reduced feed intake, and decreased milk yield (Plaizier et al., 2008). In addition, SARA can predispose animals to secondary complications such as liver abscesses, laminitis, and rumenitis, which may further compromise performance and welfare (Hernández et al., 2014). The rumen microbiota is crucial for regulating the rumen environment and metabolic rate. When ruminants are given diets that are rich in starch or easily digestible carbohydrates, the first element to be affected is the rumen microbiome. This leads to rumen dysbiosis and various additional effects. Rumen dysbiosis is a condition of imbalance compositional profile of microbiota due to microbial diversity loss, which directly affects their functionality on nutrient digestion, production, and health of ruminants (Chen et al., 2012; Firkins and Yu, 2015). This

condition is also a point where the pathogenic and opportunistic microbes are established (Petri et al., 2013). Numerous studies have demonstrated that high-concentration diet-induced SARA decreased the diversity and richness of rumen microbiota (Mao et al., 2013; Khafipour et al., 2016). However, a recent study reported no difference in microbial diversity and richness between SARA-susceptible vs. non-SARA cows (Zhang et al., 2022). The study by Zhang et al. (2022) found a higher abundance of *Prevotella*, a starch-degrading bacterium. As the starch-degrading bacteria continue to grow and the rumen pH gradually declines, rumen microbial diversity starts to fall. Concurrently, shift of several bacteria occurs; fiber-degrading bacteria such as *Bacteroidetes* phyla suppresses while *Firmicutes* phyla increases under SARA condition (Khafipour et al., 2009; Petri et al., 2013; Zhang et al., 2022).

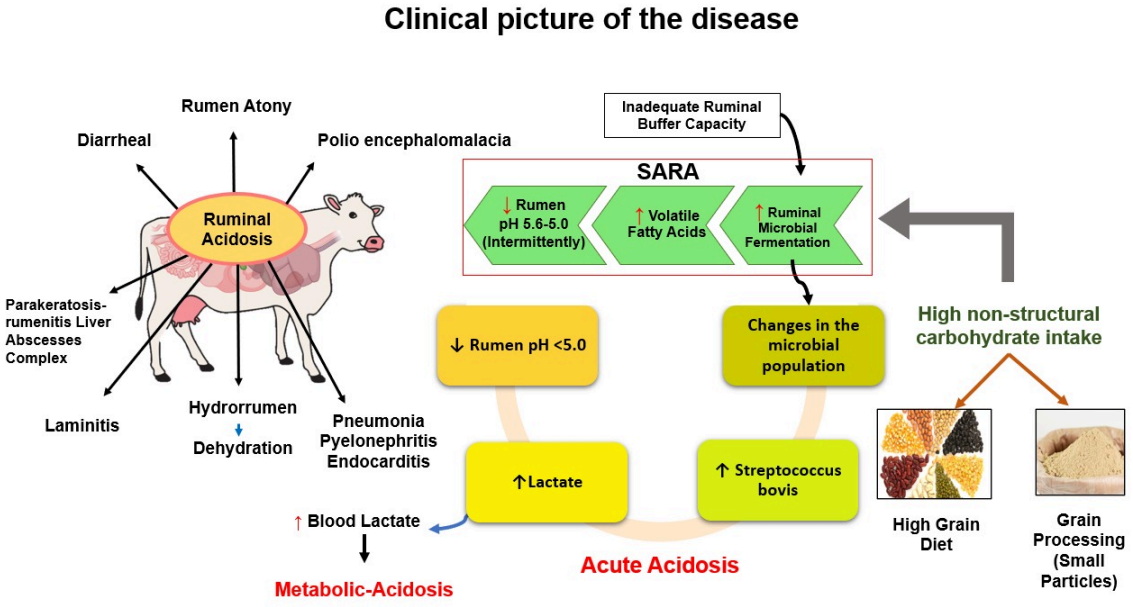

Figure 1 The effect of high-level grains and low roughage consumption in ruminants.

METHODS FOR PREVENTING AND REDUCING THE RISK OF SARA IN RUMINANT

Elevated concentrates may present several risks to ruminants. Ruminant diets with a larger proportion of highly digested carbohydrates promote a rapid decrease in rumen pH, which impairs their health and performance. Treatment with mineral buffers, zootechnical additives, vaccinations, and other additives were reported as agents for reducing ruminal acidosis (Jaramillo-López et al., 2017; Elmhadi et al., 2022). A buffer is a substance when added to an aqueous solution, effectively prevents the pH of the solution from changing when it is strongly acidic or basic. Ruminal acidosis can be mitigated by adding buffer chemicals. $NaHCO_3$, MgO, Na_2CO_3, K_2CO_3, and anhydrous limestone have all been used (Gastaldello et al., 2013). In other study, SARA could be mitigated by microbial feed additive administration (Sirisan, 2017). However, in this review, we focused on the prevention of SARA using carbonate buffer treatment.

CARBONATE BUFFER

Buffer is substance that prevents pH changes in an aqueous solution when strong acids or bases are added. Some of the chemical compounds used as rumen buffer were displayed in Figure 2. Several studies have explored various buffering agents, including $NaHCO_3$, MgO, Na_2CO_3, K_2CO_3, and anhydrous limestone, for their ability to stabilize rumen pH during SARA (Gastaldello et al., 2013). Each buffer works differently and shows varying effectiveness in adjusting rumen pH, VFA profiles, and microbial fermentation. These carbonate buffers primarily aid high-producing dairy cattle and feedlot cattle for optimal rumen function. In vitro simulations now accurately predict in vivo effects of carbonate buffer on rumen parameters (Ramos et al., 2022). Buffer also boosts lamb feedlot performance (Alhidary et al., 2019) and reduces milk fat depression in lactating cattle (Enemark, 2008). This compound also has the potential to enhance rumen microbial activity on high-grain diets (Harrison et al., 1989).

Carbonate buffers are among the most commonly used chemical agents in ruminant diets to stabilize rumen pH, especially under high-concentrate feeding systems. These compounds—such as $NaHCO_3$ and K_2CO_3 neutralized excess hydrogen ions (H^+) generated during fermentation. When rumen pH begans to fall, these buffers released bicarbonate ions (HCO_3^-) to maintain pH in the physiological range of 6.0 to 6.4, thus mitigating the risk of SARA (Cruywagen et al., 2015).

Carbonates naturally exist in soils as sparingly soluble alkaline-earth carbonates ($CaCO_3$, $CaCO_3 \cdot MgCO_3$) that dissolve rapidly. The compounds combine with Na, Ca, and Mg, forming compounds such as $NaHCO_3$, $Ca(HCO_3)_2$, $Mg(HCO_3)_2$, and $CaMg(CO_3)_2$. Most are widely used rumen buffers, maintaining ruminal pH by reducing acidity from increased VFA production, with effectiveness depending on buffer type and dosage (Tripathi et al., 2004; Sen et al., 2006). The carbonate buffer capacity is based on the equilibrium of HCO_3^-, H^+, H_2CO_3, CO_2, and H_2O. When the H^+ concentration increases, the equilibrium shifts to the right, and the dissolved CO_2 concentration increases (Russell and Chow, 1993), as shown in the following general equilibrium equation of the carbonic acid system:

$$\mathbf{HCO_3^- + H^+ \leftrightarrow H_2CO_3 \leftrightarrow CO_2 + H_2O}$$

According to previous studies, $NaHCO_3$ was the most popular buffering agent (Figure 2). The acid dissociation constant (pKa) value of an ideal buffer solution must be as close to the medium pH as possible. $NaHCO_3$ had a pKa value of 6.25, which was in the physiological pH range in the rumen. As a result, it functioned well as a buffering agent in the rumen (Ramos et al., 2021). The effects of $NaHCO_3$ supplementation on rumen environment and performance were summarized in Table 1.

Table 1 Summary of sodium bicarbonate ($NaHCO_3$) supplementation effect on rumen function and animal performance

Parameters	Effect of $NaHCO_3$ Supplementation	References
Water consumption	Increased, leading to reduced rumen viscosity and faster feed passage.	(Russell and Chow, 1993)
Rumen feed flow rate	Increased, resulting in faster rumen emptying and improved digestion/absorption of high-energy feed.	(Russell and Chow, 1993)
Rumen pH	Maintain pH in the rumen from dropping.	(Erasmus and Prinsloo, 1989; Tripathi et al., 2004; Mao et al., 2017; Neville et al., 2019; Mahdavirad et al., 2021; Vieira et al., 2024
Fiber digestibility Threshold	Rumen pH is considered suboptimal for fiber digestion.	(Tripathi et al., 2004)
Body Weight	Increased compared to the control.	(Tripathi et al., 2004)

$NaHCO_3$ was one of the most widely used buffering agents to counteract the drop in rumen pH during SARA. Its buffering action functioned by neutralizing excess H^+ ions generated during carbohydrate fermentation. The neutralization of ruminal acidity by $NaHCO_3$ occurred through its interaction with hydrogen ions (H^+) in the rumen, forming carbonic acid that subsequently dissociated into carbon dioxide (CO_2) and water (Figure 3). The dissociation of carbonic acid (H_2CO_3) in rumen epithelium produced H^+ and HCO_3^- ions, aiding pH stabilization (Aschenbach et al., 2011). According to the Stevens model (1970), CO_2 from fermentation diffused through rumen fluid and reacted with H_2O, forming H_2CO_3, which dissociated into H^+ and HCO_3^-. The released H^+ reacted with acetate to form acetic acid, while HCO_3^- diffused back into the rumen, enhancing buffering capacity. $NaHCO_3$ not only buffers acids but also influences water dynamics and ion transport. Carter (1990) described Na^+/H^+ exchange occurring at the luminal membrane, driven by Na^+-K^+ ATPase activity. Increased sodium absorption was observed as its concentration in rumen fluid rose, specifically when water intake was limited (Warner and Stacy, 1972). Furthermore, $NaHCO_3$ enhanced ruminal stability by reducing the rate of feed degradation and modifying ruminal osmolality (Russell and Chow, 1993). Systemically, bicarbonate infusion increased urinary HCO_3^- excretion, emphasizing its role in whole-body acid–base regulation (Erdman et al., 1982). Tucker et al. (1993) stated that $NaHCO_3$ delayed the postprandial decline in ruminal pH typically occurring 6 to 12 hours after feeding, possibly due to feedback mechanisms affecting salivary secretion. Bicarbonate buffering system also operated through CO_2 equilibrium in rumen. Carbon dioxide interacted with water in the epithelial cells, forming carbonic acid, which dissociated into H^+ and HCO_3^- (Aschenbach et al., 2011). This mechanism not only affected local acid–base balance but also facilitated systemic CO_2 removal through the bloodstream and pulmonary excretion.

Ruminants' need for $NaHCO_3$ varies with several factors, including salivary buffer levels, diet acidity, feed's natural buffering, ADF content, feed intake, and rumen fermentation (e.g., pH, acetate-to-propionate ratio). Production stage, forage-to-concentrate ratio, and environment have also been reported to play an essential role (Aslam, 1991). In addition, $NaHCO_3$ supplementation can alter animal behavior and digestion. Vicente et al. (2022) reported that the compound reduced the time spent swallowing, chewing, and ruminating per gram of dry matter. Similarly, Deswysen et al. (1987) observed that $NaHCO_3$ increased the rate of rumen passage and emptying, thereby enhancing dry matter intake over time.

Buffer	Number of articles	References
MgO	1	(Agustinho et al., 2022)
$CaMg(CO_3)_2$	1	(Agustinho et al., 2022)
$KHCO_3$	1	(Alfonso-Avila et al., 2017)
KCl	1	(Alfonso-Avila et al., 2017)
Na_2CO_3	1	(Alfonso-Avila et al., 2017)
H_3PO_3	1	(Esdale and Satter, 1972)
$CaHPO_4$	1	(Hall & Thomas, 1984)
$Na_4P_2O_7$	1	(Hall & Thomas, 1984)
NaCl	1	(Rogers et al., 1982)
$Na_3H(CO_3)_2$	1	(Mahdavirad et al., 2021)
K_2CO_3	2	(Alfonso-Avila et al., 2017); (Dion et al., 2021)
$CaCO_3$	3	(Hall and Thomas, 1984); (Clark et al., 1989); (Neiderfer et al., 2020)
$NaHCO_3$	13	(Kilmer et al., 1981); (Rogers et al., 1982); (Hall and Thomas, 1984); (Rogers et al., 1985); (Jacques et al., 1986); (Erasmus and Prinsloo, 1989); (Tucker et al., 1992); (Bach et al., 2018); (Neville et al., 2019); (Cruywagen et al., 2015); (Neiderfer et al., 2020); (Mahdavirad et al., 2021); (Vicente et al., 2022)

Figure 2 Some widely used buffers for ruminant.

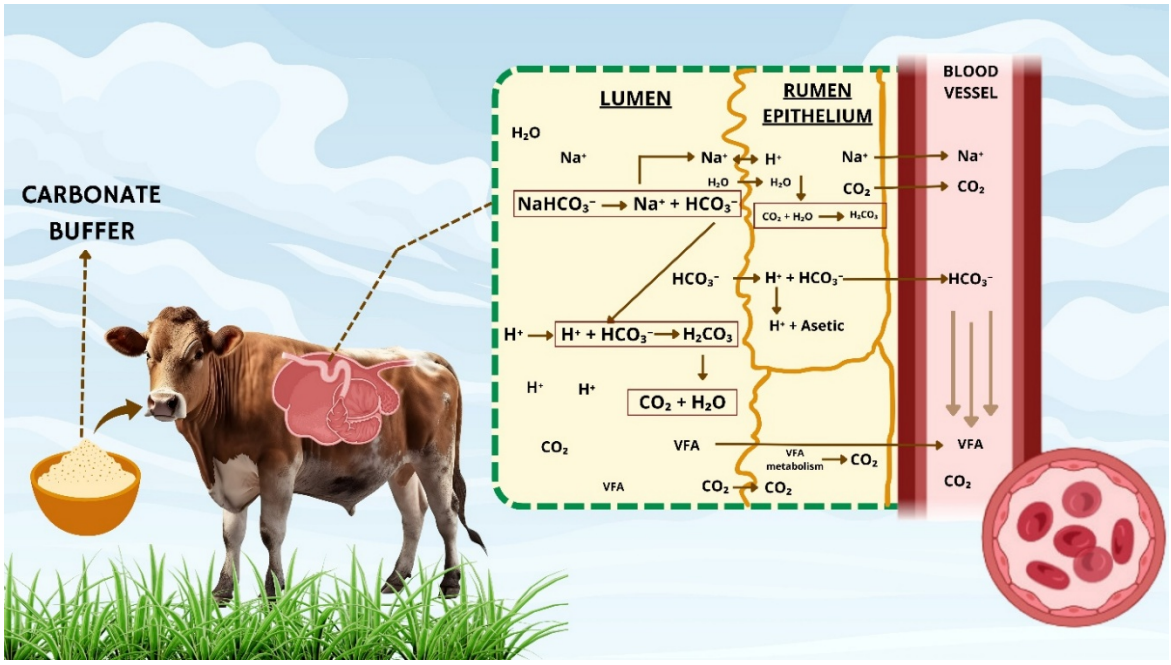

Figure 3 A brief overview of the sodium bicarbonate ($NaHCO_3$) buffer in the rumen.

The effect of carbonate buffer in ruminal pH and fermentation

Rumen pH plays a crucial role in optimizing nutrient digestibility within the ruminant body (Calsamiglia et al., 2008; Jones et al., 2016). Rumen pH is never above 6.15, with poor treatment (Cruywagen et al., 2015). A dropping in rumen pH lower than 5.6 for exceeding 3 h/d in a row (Gozho et al., 2005) or for 111 to 180 minutes per day from pH 5.5 to 5.0 (Jaramillo-López et al., 2017) is defined as SARA. The normal pH should be between 5.8 and 6.4 to keep the rumen population in balance (Ishler et al., 1996). Prolonged period of rumen pH depression can have many problems and negatively alter rumen microbial (Elmhadi et al., 2022).

Several studies have publicized supplementation buffers for ruminants to elevate rumen pH (Table 2). A previous study reported that lactating Holstein cows that were given a ruminal cannulate and high-concentrate diet. After continuous infusion of 9 to 12 moles of $NaHCO_3$ into rumen, pH increased from 5.5 to 6.2 and the ratio of acetate : propionate grew up starting with 1.1 to 2.8 (Esdale and Satter, 1972). Johnson et al. (1988) adding 1% $NaHCO_3$ on basal diet containing 50:50 grain to forage resulted in no effect on pH. Erdman (1988) summarized the advantages of applying $NaHCO_3$ and K_2CO_3 as buffers could keep ruminal pH steadily stable. In other research have reported pH increasing with adding $NaHCO_3$ on ration contain low fiber and high concentrates (Rogers et al., 1982; Mao et al., 2017). The administration of $NaHCO_3$ and Na_4P20_7 in the diet with high concentrate can maintenance pH higher than the control for 24 hours, but both neither of these buffers-maintained pH of 6.8 (Hall and Thomas, 1984). $NaHCO_3$ to the Holstein diet decreased the amount H^+ ion from 0 to 6 h after feeding in the rumen fluid (Tucker et al., 1992), which indicates elevated pH rumen. Pérez-Ruchel et al. (2014) reported that the addition of 20 g/kg DMI of a mixture of 75: 25 $NaHCO_3$ and MgO to the pasture-raised sheep resulted in a high ruminal pH. Furthermore, both low fermentation activities and ruminal ammonia, which enhanced the passage rate and transit led to more purine derivatives being passed in urine.

Cruywagen et al. (2015) found that the administration of $NaHCO_3$ on a basal diet formulated for potential acidosis to induce SARA (35.2 % forage 64.8 % concentrate) had a shorter rumen pH of 5.5 carbonate (7.5 hours) than control (13.8 hours). Furthermore, the addition of 3.2% K_2CO_3 in the dairy cattle diet made rumen pH increase linearly (Fraley et al., 2015). Neville et al. (2019) revealed that supplementation with some buffer, i.e., calcareous marine algae (CMA), marine magnesium oxide (MM), and sodium bicarbonate (SB). During the 2 to 4 h period, the control treatment cows had a lower mean rumen pH compared with CMA, CMA+MM, and SB. Controls tended to have lower daily (24 h) mean rumen pH values than SB, and both CMA and CMA+MM maintained a greater daily (24 h) (Figure 4).

Table 2 Effect of supplementation of carbonate buffer in rumen fermentation, digestibility, and milk quality

Animal/breed	Potention diet-induced acidosis*	Buffer Treatments	Rumen fermentation Change*		Digestibility and Intake Change*		Quality of milk production and Quality*		Literature/Citation
			Effect on Ruminal pH	Total VFA	Digesti-bility	Feed Intake	Milk Production	Milk Quality (Fat)	
Goat / Alpine	✗	K_2CO_3 (1.6%)	=	=	NR	=	=	=	(Dion et al., 2021)
Arabic lambs	✓	$NaHCO_3$ (1.5%)	↑	=	=	=	NR	NR	(Mahdavirad et al., 2021)
		$Na_3H(CO_3)_2$ (1.5%)	↑	=	=	=	NR	NR	
		$NaHCO_3$ (0.75%) + $Na_3H(CO_3)_2$ (0.75%)	=	=	=	=	NR	NR	
Cow / Holstein	✓	$NaHCO_3$ (0,7%)	↑	NR	NR	↑	=	↑	(Neville et al., 2019)
Cow/Holstein	✓	$NaHCO_3$ (200g/day)	=	=	=	=	=	=	(Neiderfer et al., 2020)
		$CaCO_3$ (200g/day)	=	=	=	=	=	=	
		$NaHCO_3$ (200g/day)	=	=	=	=	=	=	
Cow/Holstein	✓	$NaHCO_3$ (0.8%)	=	NR	NR	=	=	=	(Bach et al., 2018)
Cow/Holstein	✓	K_2CO_3 (1.8%)	=	=	NR	=	=	=	(Alfonso-Avila et al., 2017)
		$KHCO_3$ (2.8%)	=	=	NR	=	=	=	
		Na_2CO_3 (1.4%)	=	=	NR	=	=	=	
Cow/ Holstein	✓	$NaHCO_3$ 70 mg/g in ration	↑	↑	NR	NR	NR	NR	(Mao et al., 2017)
Cow/Holstein	✓	$NaHCO_3$ (0.8%)	=	=	NR	=	↑	↑	(Cruywagen et al., 2015)
Lamb/ Malpura weaner	✓	$NaHCO_3$ 7.5 g/day	↑	NR	=	=	NR	NR	(Tripathi et al. 2004)
		$NaHCO_3$ 15 g/day	↑	NR	=	=	NR	NR	
		$NaHCO_3$ 22.5 g/day	↑	NR	=	=	NR	NR	
Cow/Holstein	✓	$NaHCO_3$ (1.5%)	NR	NR	NR	=	=	=	(Tucker et al., 1992)
Cow/Holstein	✓	$NaHCO_3$ (1.2%)	↑	=	NR	=	=	=	(Erasmus and Prinsloo, 1989)
Cow/Holstein	✓	H-white $CaCO_3$ (1.4%)	=	=	NR	↓	=	=	(Clark et al., 1989)
		Reagent grade $CaCO_3$ (1.4%)	=	=	NR	↓	=	=	
		Reagent grade $CaCO_3$ (2.1%)	=	=	NR	↓	=	=	
Cow/Holstein	✗	$NaHCO_3$ (1%)	=	=	=	=	=	=	(Johnson et al., 1988)
Cow/Holstein	✗	$NaHCO_3$ (1%)	=	=	=	=	NR	NR	(Jacques et al., 1986)
Dairy cow	✓	$NaHCO_3$ (1.2%)	=	=	NR	=	=	=	(Rogers et al., 1985)
Cow/ Holstein	✓	$NaHCO_3$ (20g/kg diet)	=	=	=	=	=	=	(Rogers et al., 1982)
Cow/Holstein	✗	$NaHCO_3$ (0,8%)	=	=	NR	=	=	NR	(Kilmer et al., 1981)
Cow/Holstein	✓	$NaHCO_3$ (5%)	=	=	NR	NR	NR	NR	(Esdale and Satter, 1972)

NR, Not reported; *, Effect of treatments compared with control

✓ High concentrate or presentation concentrate on ration more than 50 %
✗ Low concentrate or the diets do not induce acidosis
↑ Increase
= Similar with control
↓ Decrease

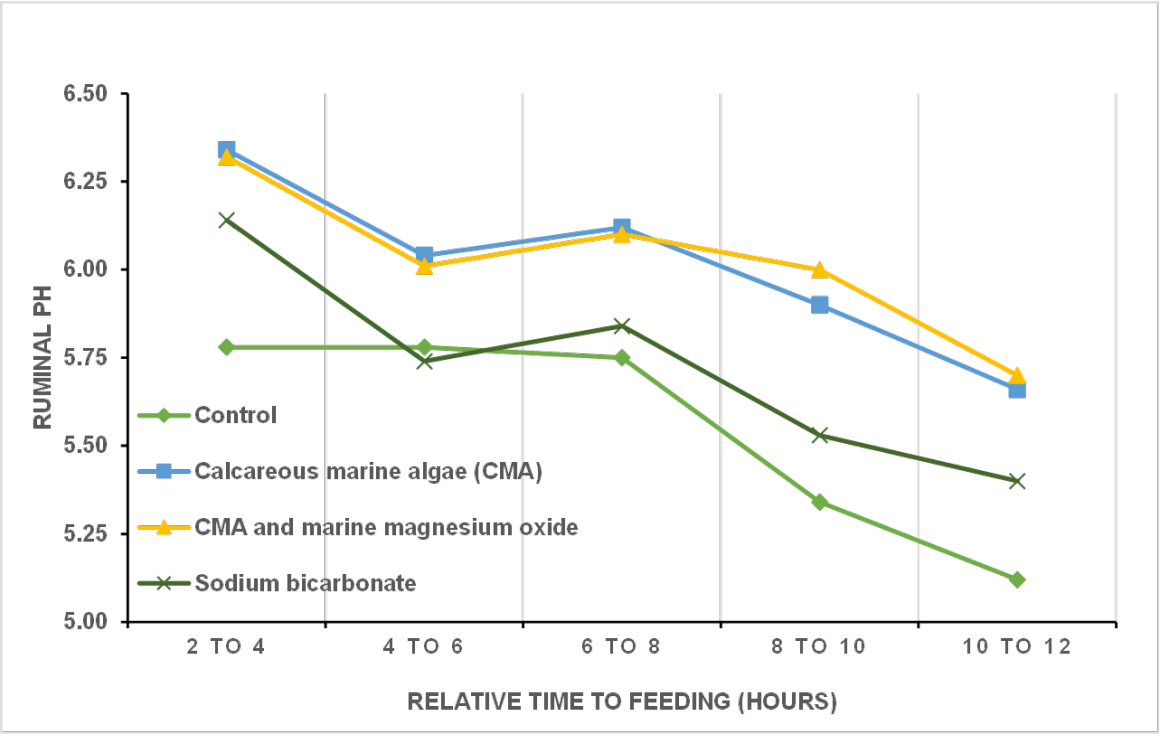

Figure 4 Effect of calcareous marine phytoplankton, with or without marine magnesium oxide, and sodium bicarbonate on the mean rumen pH over a two-hour feeding period (rumen pH). Data derivate from Neville et al. (2019).

The administration of buffer $NaHCO_3$ infusion trends to enhance total VFA in the rumen (Tucker et al., 1993). Cruywagen et al. (2015) reported that the total VFA of rumen Holstein treated by 0.8% $NaHCO_3$ was higher than the control (119.8 vs. 112.9 mM). Ruminal VFA was increased by adding 1.2 % $NaHCO_3$ into a high level of dietary concentrate (75%) in the diet (Kennelly et al., 1999; Khorasani and Kennelly, 2001). Those described as a result of the high concentration of VFA alongside the increase in acetate. However, some studies showed different results. In addition of $NaHCO_3$ in the diet did not affect ruminal VFA concentration (Kilmer et al., 1981; Johnson et al., 1988). On the other hand, Erdman et al. (1982) and Rogers et al. (1982) stated that the administration of $NaHCO_3$ in the diet had more acetate and less propionate in the rumen. The inconsistent effects of $NaHCO_3$ supplementation on ruminal VFA profiles observed across studies could be attributed to differences in diet composition, particularly the forage-to-concentrate ratio. In studies where cattle were fed a 50:50 forage-to-concentrate diet (Kilmer et al., 1981; Johnson et al., 1988), $NaHCO_3$ supplementation had little to no effect on the molar proportions of acetate and propionate. However, in trials using high-concentrate diet, such as 75:25 and 60:40 concentrate-to-forage ratios (Rogers et al., 1982; Erdman et al., 1982, respectively), $NaHCO_3$ tended to increase the proportion of acetate and decrease propionate in the rumen. Mao et al. (2017) showed that administration of $NaHCO_3$ enhanced acetate, propionate, iso-butyrate, isovalerate, and valerate concentrations, but decreased butyrate and the level of fatty acids. Cows receiving the buffer diet observed had higher rumen acetate values (Cruywagen et al., 2015).

According Xu et al. (1994) inclusion buffer Rumen 8® (Agchem Commission Co. Princeton, New Jersey, USA) containing 36.3% Na_2C0_3 and 26.5% $NaHC0_3$ or Alkaten® (Church and Dwight, Co., Princeton, New Jersey, USA) containing 43.4 % Na_2C0_3 and 34.4 % $NaHC0_3$ at 2.2% in high level concentrate diet (60%) resulted in lower rumen acetate: propionate ratio concentration than without buffer treatment due to an increase in propionate concentration. This was consistent with

the result of Cruywagen et al. (2015), showing that the concentration of ruminal propionic acid that had $NaHCO_3$ in the diet was higher than control. However, there was a difference in the ruminal concentration of butyrate. The administration of $NaHCO_3$ in high-level concentrate diet had higher butyrate concentration than control (Kennelly et al., 1999; Khorasani and Kennelly, 2001; Cruywagen et al., 2015). The addition of 1.2% $NaHCO_3$ increased ruminal pH and liquid dilution rate, which decreased the molar percentage of ruminal propionic (Erasmus and Prinsloo, 1989).

Supplementation of $NaHCO_3$ positively affects the reduction of bioamine level, the elevation of pH rumen, and the modification of microbes ecology (Mao et al., 2017). Tun et al. (2020) studies using quantitative PCR (qPCR) and showed that SARA stimulated numerous species of rumen microbes by increasing or tending to increase protein metabolism and aromatic compound metabolism. Mao et al. (2013) reported that SARA enhanced the bacteria population utilizing starch and glucose and diminished fibrolytic bacteria. According to Calsamiglia et al. (2012), fibrolytic activity bacteria would be depressed at a pH below 5.8; meanwhile, ruminal pH at 5.2 to 6 was the condition of active activity of amylolytic bacteria (Ishler et al., 1996). Supplemented $NaHCO_3$ at 70 mg/g in the diet could increase the diversity of ruminal bacteria such as *Ruminococcus*, *Succinivibrio*, and *Prevotella* while depressed *Streptococcus* and *Butyrivibrio* bacteria (Mao et al., 2017).

$NaHCO_3$ has a potency as ruminal buffer supplement that could maintain ruminal pH in a suitable range unless for bacteria and also for protozoa activity. This is possible because relationship among the lowest level of ruminal pH and the ruminal protozoa. Supplemented $NaHCO_3$ at 25, 50, and 75 g increased the ruminal protozoa compared to without $NaHCO_3$ supplementation into diet (Newbold et al., 1991). Philippeau et al. (2017) reported populations of ruminal protozoa were reduced while ruminal pH levels at < 6. Mahdavirad et al. (2021) reported that the addition of 1.5% $NaHCO_3$, 0.75% $NaHCO_3$ combined with 0.75% sodium sesquicarbonate, and 2% zeolite to the feed increased the population of rumen protozoa compared with the control. Santra et al. (2003) also resulted, inclusion of 2.25% $NaHCO_3$ in high level of concentrate diet had no effect on the protozoa population in the sheep rumen. However, the addition of $NaHCO_3$ improves the population of rumen protozoa than the control treatment. In contrast to the findings of Montaño et al. (1999), $NaHCO_3$ addition to the bull's diet increases rumen pH and reduces protozoa populations.

Ruminal ammonia (NH_3) was not affected by adding $NaHCO_3$ (Johnson et al., 1988). Kilmer et al. (1981) and Okeke et al. (1983) showed that diets containing $NaHCO_3$ in lactating cattle could also detect increases in NH_3. Although some studies, such as Kilmer et al. (1981), demonstrated that $NaHCO_3$ supplementation increased ruminal NH_3 concentrations due to enhanced protein solubility and deamination from elevated rumen pH. Johnson et al. (1988) reported a different outcome, suggesting that protein degradation was limited or that microbial assimilation of ammonia was efficient, thereby masking the effect of $NaHCO_3$. This was supported by their observation that $NaHCO_3$ had no significant impact on apparent nutrient digestibility. However, there was limited data to discuss supplementation of Na_2CO_3 or another buffer to ruminal NH_3.

Carbonate buffers commonly used in ruminant diets included $NaHCO_3$. The optimal effect on ruminal pH was observed with $NaHCO_3$ supplementation ranging from 0.7% to 1.5% of diet, or at levels of 20g/kg DMI, which increased pH values from approximately 5.5 to above 6.0. This range appeared to support favorable fermentation conditions by increasing acetate proportions and, in some cases, total VFA concentrations. However, the response of VFA profiles to buffer addition varied depending on the forage-to-concentrate ratio and buffer composition. In diets with high-concentrate (≥ 60%), $NaHCO_3$ increased acetate and decreased propionate, while in 50:50 diets, the effect was minimal. $NaHCO_3$ supplementation modulated rumen microbial ecology by enhancing the population of fibrolytic

bacteria and protozoa, while decreasing lactic acid-producing bacteria. These microbial changes were essential to stabilizing fermentation and preventing pH drops. Although results on ruminal NH_3 concentrations remained inconsistent, the inclusion of $NaHCO_3$ generally supported a more stable ruminal environment.

The influence of buffer carbonate in the feed intake and nutrient digestibility

The influence of buffer addition on diet has been investigated by previous studies (Table 2). Rogers et al. (1982) explained the addition of 20g $NaHCO_3$ / kg diet in high grain ration enhanced digestibility of dry matter (DM), organic matter (OM), and ADF in Holstein. This study contradicts Johnson et al. (1988) and Jacques et al. (1986), who reported that the administration of 1% $NaHCO_3$ for Holstein cows had no effect on the nutrient digestibility, such as DM, OM, crude protein (CP), and ADF. In addition, the digestibility did not differ between the administration of 1% $NaHCO_3$ in diet containing 50% and 84% silage diets (Jacques et al., 1986). However, water consumption (L/d) tended to be higher for cows receiving 1% $NaHCO_3$ (Johnson et al., 1988).

Studies on lambs reported similar results. Mahdavirad et al. (2021) demonstrated that the utilisation of various buffering sources such as 2% zeolite, 1.5% $NaHCO_3$, and 1.5% sodium sesquicarbonate did not affect the apparent digestibility of DM, OM, CP, NDF, and ADF. The finding of that investigation was the same as reported in the other study, i.e., the inclusion of 1% $NaHCO_3$ (Boerner et al., 1987), 1.4% zeolite (Dschaak et al., 2010), and 0.75% $NaHCO_3$ (Doepel and Hayirli, 2011; Perez-Ruchel et al., 2014) as a buffering agent in the diet of ruminants (cattle and sheep) has no positive effects on the apparent digestibility of DM, OM, and CP significantly. Dschaak et al. (2010) reported that the addition of 1.4% zeolite or $NaHCO_3$ did not affect the digestibility of DM, OM, NDF, and ADF. However, several studies showed that the inclusion of 0.65% sodium sesquicarbonate (Solorzano et al., 1989), 1.5% $NaHCO_3$ (Askar et al., 2011), and 1% $NaHCO_3$ (Gastaldello et al., 2013) into the diet enhanced the apparent digestibility of DM, OM, and CP. The inclusion of 1% $NaHCO_3$ or 1.3% limestone into the diet (consisting of 90% concentrate) resulted in significant improvement in the digestibility of DM, OM, and CP (Gastaldello et al., 2013). Vicente et al. (2022) concluded that adding 2% $NaHCO_3$ was the appropriate strategy in the lamb diet with high grain (corn base) and no fiber source.

Administration of 0.8% $NaHCO_3$ did not reduce feed intake (Bach et al., 2018). Another type of buffer, such as the addition of 1.4% $CaCO_3$ in high-concentrate, decreased DMI of cattle (Clark et al., 1989). Adding 1.8% K_2CO_3 for cattle tended to decrease body weight when compared to the control group (Alfonso-Avila et al., 2017). The addition of various buffering sources, namely 1.5% $NaHCO_3$ and 1.5% sodium sesquicarbonate, did not result in any significant differences in each treatment on final weight, average daily gain (ADG), DMI, and feed conversion ratio (FCR) (Mahdavirad et al., 2021). The study conducted by Doepel and Hayirli (2011) found that supplementation with 0.75% $NaHCO_3$ in the diet of Holstein cattle did not result in a significant increase in dry matter intake (21.0 kg/d), milk yield (30.8 kg/d), or milk components, including fat (1.16 kg/d), protein (1.01 kg/d), and lactose (1.40 kg/d). Hu and Murphy (2004) in their meta-analysis demonstrated that increasing Na_2CO_3 in the feed by up to 400 mEq/kg could enhance DMI and milk production. The administration 150 to 500 mEq/kg (DM basis) Na_2CO_3 for Holstein cows increase (DMI) throughout the lactation period (Correa et al., 2014).

Findings from Alhidary et al. (2019) indicate that adding a 0.4% mixture of acid buffer and Na_2CO_3 (50:50 w/w) in the feed of Awassi lambs can reduce FCR by 5.46%. Nevertheless, it is not showing any difference in ADG, DMI, and final body weight compared to the control group. Otherwise, according to Mahdavirad

et al. (2021) Adding 1.5% Na_2CO_3 to the Arabi lambs' diet did not statistically affect ADG, DMI, BW, or FCR.

The impact of buffer carbonate on ruminant performance and quality product

For several decades, numerous studies have explored the effects of various buffer treatments on milk yield and composition (Table 2). Rogers et al. (1982) and Johnson et al. (1988) show that daily milk yield was not affected by the administration of $NaHCO_3$. The treatments included a control group (CON), administration with a combination of 125 g/day of $CaCO_3$ and 75 g/day of magnesium oxide (FCCM), 200 g/day of calcium carbonate (FCC) or sodium bicarbonate (FSB), as well as abomasal infusion of a lipid encapsulate providing 200 g/day of sodium bicarbonate (ISB) in diet Holstein. The results indicated that none of the treatments had a significant influence on the milk yield or composition (Neiderfer et al., 2020). The inclusion of $CaCO_3$ as much as 1.4 until 2.1% to Holstein diets containing concentrate and corn silage (60% : 40% (DM basis)) resulted in a reduction in milk yield and showed no significant impact on the synthesis of milk fat and milk protein in dairy cows (Clark et al., 1989). Johnson et al. (1988) reported that adding 1% $NaHCO_3$ did not affect milk fat or protein composition. However, various studies have yielded varying outcomes.

Erasmus and Prinsloo (1989) observed that the inclusion of 1.2% $NaHCO_3$ resulted in a tendency towards an increase in fat percentage and yield of 4% FCM. The inclusion of rumen buffering products (marine, MgO, $NaHCO_3$, calcareous marine algae) in lactation dairy cattle diet, an increasing in milk fat and protein output can be achieved (Neville et al., 2019). Adding $NaHCO_3$ (Cruywagen et al., 2015) and K_2CO_3 (Alfonso-Avila et al., 2017) in high-concentrate diets resulted in an enhancement synthesis of milk fat. The specific mechanism responsible for this effect remains to be determined. The trans-10 18:1 milk fat concentration increased significantly in response the administration 1.4% Na_2CO_3 compared with 1.8% K_2CO_3 (Alfonso-Avila et al., 2017). Nonetheless, in comparison the 2.8% $KHCO_3$, 2% KCl, 1.8% K_2CO_3, and the control, they have not significant effect on either milk protein or production. According to Alfonso-Avila et al. (2017) supplementation of 1.8% K_2CO_3 on dairy cattle diet caused higher protein content in the milk compared with supplementation 1.4% Na_2CO_3. Bach et al. (2018) stated that the administration of 0.8% $NaHCO_3$ is effective in maintaining milk production; however, it does not serve as a preventive measure against reduced feed intake. Administration of 0.8% $NaHCO_3$ in the diet of Holstein cows resulted in higher milk yield/kg DMI compared to the control group (Cruywagen et al., 2015). This variability of response to dietary 1% $NaHCO_3$ could be due to differences in diet formulation, amounts of $NaHCO_3$, and stage of lactation (Johnson et al., 1988).

There are several studies on giving buffers for fattening that have been carried out by previous researchers. Toprak et al. (2016) stated that the administration of micronized zeolite until 2% in a diet of fattening lambs did not have significant impact on the ADG or the final body weight. Supplementary buffering agent (0.4% mixture of acid buffer and Na_2CO_3 (50:50 w/w) on Awassi lambs' diet improved carcass characteristic and also reducing the body fat (Alhidary et al., 2019). In addition, they explained that meat color in supplementation 0.4% Celtic Sea Minerals (commercial product) or 0.4% WMC Seaweed (commercial) were higher than control group. Supplementation different concentration of $NaHCO_3$ into lamb diet containing high concentrate did not have differences on carcass composition (Sen et al., 2006). But The combination of MgO and $NaHCO_3$ improved total tract nutrient digestibility, rumen fermentation, and serum antioxidant levels in lambs, leading to enhanced growth and carcass quality (Xiong et al., 2024).

Thus, animal performance is determined by various factor such as nutrient concentration, feed intake, digestibility, and metabolic efficiency of absorbed nutrients. The variation of findings from different studies may be attributed to differences in buffer level, type, and purity, as well as the variations in diets composition and experimental conditions (Mahdavirad et al., 2021).

FUTURE RESEARCH DIRECTIONS AND INNOVATIONS

Maintaining optimal ruminal pH is essential for the health and productivity of ruminants. Buffer carbonates, such as $NaHCO_3$, play a significant role in stabilizing rumen pH and preventing issues like subacute ruminal acidosis (SARA). Future research and innovation in this area should aim to improve the efficacy and sustainability of buffer carbonate use in ruminant nutrition, as well as integrate these buffers into precision livestock farming systems. For instance, developing rumen buffer products that manage pH fluctuations and support enzyme activity, or creating buffer formulations that are easily absorbed, could enhance their effectiveness and promote a healthier rumen environment. Encapsulation of buffer or slow-release technology can be designed to release buffer substances gradually, thereby maintaining rumen pH stability more effectively. Research in this area is still limited, especially on the development of encapsulation for rumen buffers. The study by Neiderfer et al. (2020) found that supplementing feed with encapsulated $NaHCO_3$ improved hindgut fermentation, as evidenced by an increase in fecal pH, a decrease in fecal volatile fatty acids (VFAs), and a reduction in fecal lipopolysaccharides (LPS). Exploring sustainable and environmentally friendly sources of carbonate buffers, such as by-products from other industries or natural minerals, can help reduce reliance on synthetic additives. Additionally, conducting in-depth observations on how carbonate buffers affect rumen microbiome composition and function, identifying beneficial microbial shifts that contribute to pH stability, would be highly valuable. Using an omics approach to investigate these changes would enable a comprehensive and detailed understanding, providing insights into the overall mechanisms involved.

CONCLUSION

Feeding high-concentrate diet can be used to optimize the performance and efficiency of ruminant livestock. The risk of feeding high-concentrate diet was the occurrence of SARA in ruminants. Methods for preventing and reducing the risk of SARA in ruminant livestock include the administration of carbonate compounds. The administration of carbonate compounds to ruminant livestock, either singly or in combination, functions as a buffer to maintain rumen pH, ensuring that SARA does not occur. Based on the reviewed studies, supplementation of carbonate buffer especially $NaHCO_3$ at levels between 0.7% to 1.5% of ruminant diet has been shown to help stabilize ruminal pH**,** reduce the risk of SARA**,** and support efficient rumen fermentation**.**

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AUTHOR CONTRIBUTIONS

Ulvi Fitri Handayani: Conceptualization (equal); writing – original draft preparation (lead); Writing – review & editing (lead); Visualization (lead).
Ahmad Sofyan: Supervision (lead); conceptualization (lead), writing – original draft (equal), and Writing – review & editing (equal); Validation (lead).
Wulandari: Conceptualization (supporting); Writing – original draft preparation (equal); writing – review & editing (equal).
Mohammad Miftakhus Sholikin: Conceptualization (supporting); Writing – original draft preparation (equal); writing – review & editing (equal).
Muhammad Ainsyar Harahap: Conceptualization (supporting); Writing – original draft preparation (equal).
Slamet Widodo: Conceptualization (supporting); Writing – original draft preparation (equal).
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Agung Irawan: Validation (equal) and Writing – review and editing (equal).
Hendra Herdian: Writing – review & editing (supporting).
Awistaros Angger Sakti: Writing – review & editing (supporting).
Yelsi Listiana Dewi: Writing – review & editing (equal).
Gunawan: Writing – review & editing (supporting).
Lili Anggraini: Writing – review & editing (supporting).
Latifah: Writing – review & editing (supporting).
Bima Putra Pratama: Visualization (equal), Writing – review & editing (supporting).
Ahmad Zein Baihaqi: Writing – review & editing (equal).

CONFLICT OF INTEREST

The authors declare that they have no competing interest.

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