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Nutrient Synchrony: Is it a Suitable Strategy to Improve Nitrogen Utilization and Animal Performance?*

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ABSTRACT : The objective of this paper was to review recent studies on nutrient synchrony and the effects of synchronization of energy and N supply in the rumen on nitrogen utilization and animal performance. Theoretically, synchronization of energy and N supply in the rumen should allow more efficient use of nutrients by rumen microbes, increase microbial protein and fermentation end products, and thus increase available nutrients in the small intestine. Efficient use of nutrients possibly improves animal performance and reduces nutrient excretion to the environment. However, a number of studies showed contradictory results in microbial protein synthesis, nitrogen retention and animal production performance. Since there are additional challenges to nutrient synchrony that must be addressed, further research is required to apply the nutrient synchrony concept directly to the field situation. (**Key Words :** Nutrient Synchrony, N Utilization, Ruminants, Performance)

INTRODUCTION

An excessive supply of feed nutrients results in an increase in waste excreted to the environment. The possible environmental pollutants produced by livestock are nitrogen, phosphorus and other organic compounds (e.g., methane and nitrous oxide). Excretion of these components to the environment may be increased by inefficient digestion and metabolism of the ruminant animal, and much of the inefficiency may occur in the rumen due to complicated and competitive metabolic pathways of rumen microbiota (Russell, 2002). In ruminants, actual digestion by the enzymes secreted by the host animal occurs after rumen microbes have modified feed nutrients into different forms (e.g. volatile fatty acids, ammonia and microbial protein). Digestion and metabolism of ruminants, thus, depend much on rumen microbial metabolism (Khezri et al., 2009). Therefore, better understanding and subsequent manipulation of rumen function is a prerequisite for efficient animal production (milk or meat) and for lower nutrient losses during digestion and metabolism.

An adequate but not excessive nitrogen (N) supply to support the animal's requirement has been one of the biggest concerns in our industry because protein sources are the most expensive ingredients in animal diets. Non-excessive N supply to the animal becomes more important since the amounts of N excreted in animal manure have increased markedly during recent decades, causing unacceptable air and water pollution (Hristov et al., 2005). In dairy cows, inefficient N utilization caused the loss of N in urine while the amount of N excretion in faeces was relatively constant (Castillo et al., 2001). Therefore, any measures to increase N utilization of ruminants would reduce urinary N excretion. Improved efficiency of microbial protein synthesis (MPS) is considered as the most important target to maximize MPS, while synchronization of carbohydrate and protein supply in the rumen has been suggested as one possible solution to achieve this (Kaswari et al., 2007).

The term "synchrony" derived from Greek roots for "together" and "time," means simultaneous occurrences in general (Hall et al., 2008). In ruminant nutrition, "synchrony" means providing both rumen degradable protein (RDP; non protein N and rumen degradable true

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protein) and energy (ruminally fermentable carbohydrates) to the rumen, so that ruminal microorganisms use both simultaneously. The synchronization of the ruminal degradation rate of carbohydrates and protein has been proposed as a method to increase ruminal MPS, improve efficiency of N usage and animal performance, and decrease urinary N excretion (Cole et al., 2008). Synchronous supply of energy and N to the rumen enhanced the efficiency of microbes in capturing N and use of ATP for microbial growth (Johnson, 1976; Herrera-Saldana et al., 1990; Sinclair et al., 1991; 1993; Richardson et al., 2003), which implied synchronized feeds increased microbial protein production in the rumen and enhanced rumen fermentation efficiency, and thereby improved feed utilization and animal performance (Chumpawadee et al., 2006).

A number of studies have been conducted to evaluate the effects of synchronization of energy and N supplied in the rumen using various systems. There is supportive evidence indicating that the synchronous supply of energy and nitrogen in the rumen is beneficial in terms of efficient utilization of nutrients by ruminants; however, conflicting results have also been reported. In this paper, we reviewed the possible ways of achieving synchronization of energy and N supply in the rumen and the effects of synchrony on rumen function, MPS and performance of ruminant animals.

METHODS FOR SYNCHRONIZATION OF DIETARY ENERGY AND PROTEIN IN THE RUMEN

Several ways to supply energy and N to the rumen synchronously have been reported in the literature. Some examples are: i) Exchange of feed ingredients; ii) Supplementation of energy or protein sources; iii) Using index values and iv) Change in feeding frequency or pattern. Changing feed ingredients or composition could achieve synchronization of energy and N supply to the rumen. For example, changing the concentrate:forage ratio is a traditional way of manipulating synchronicity of a feed. However, some other factors (i.e. level of forage intake and its fermentation rate, and composition of concentrate and its associative effect on forage digestibility) make it difficult to distinguish a synchrony effect from effects caused by other factors (Cabrita et al., 2006). A change in feed ingredients alters the amount of organic matter and nitrogen and their fermentation rate in the rumen, which may influence extent of synchronicity in the rumen. Rotger et al. (2006) synchronized energy and N supply to the rumen by changing feed composition and formulated the diets with three different synchronicity combinations (fast fermentable synchronicity, slow fermentable synchronicity and asynchronicity).

Synchrony achieved by energy or N supplementation also resulted in a positive effect on MPS (Lardy et al., 2004; Elseed, 2005). Particularly in forage-fed ruminants, supplementation of energy or N sources can improve rumen fermentation since carbohydrate and N degradation rates in forages are normally imbalanced (Van Soest, 1994). Nutrient supplementation may enhance rumen microbial population and VFA production (Mould et al., 1983). Hersom (2008) suggested several strategies to elicit optimal synchrony. The most frequently applied supplementation strategies are controlling the timing of feed offering, the form of nutrients supplied and supplement types and the balance of energy to protein ratio (Hersom, 2008). In a number of experiments using mature cows, forage quality was an important factor for successful nutrient synchrony effects. Low quality forage with frequent supplementation tended to increase the positive effect of nutrient synchrony (Hersom, 2008) more than with high quality forages.

Another possible way is to develop a synchrony index (SI). A number of experiments have used SI to scale synchronization of energy and N release in the rumen. Sinclair et al. (1993) used CP and OM degradabilities of dietary ingredients and determined SI by using *in situ* data and 25 g of N/kg truly rumen digested OM was assumed to be the optimum synchrony between N and OM (Czerwaski, 1986). When carbohydrate rather than OM was used, 32 g N/kg carbohydrate degraded in the rumen was used instead (Sinclair et al., 1991). The value of 1.0 SI represents perfect synchrony between energy and N supply throughout the day, while values <1.0 indicate the degree of asynchrony (Sinclair et al., 1993). The SI proposed by Sinclair et al. (1993) may be useful to estimate nutrient synchrony of feeds (Cole et al., 2008). However, since the *in situ* method used to calculate SI is influenced by many factors, such as animal, nylon bags and feedstuff characteristics (Madsen and Hvelplund, 1994; Huhtanen, 2005), the SI of a feed may not well represent the effect of the feed on animal production or MPS. A new diet evaluation system using protein balance in the rumen has been developed in the Netherlands (Ichinohe et al., 2008). The OEB (degradable protein balance in the Dutch system) value shows the balance between microbial protein synthesis potentially possible from ruminal degradable crude protein and from the energy extracted during anaerobic fermentation in the rumen (Tamminga et al., 1994). When the OEB value is >0, potential loss of N from the rumen occurs, whilst a value lower than 0 means more ruminal degradable CP is required for microbial activity (Valkeners et al., 2004).

Although changing feed ingredients or nutrient supplementation could regulate the synchronicity between energy and N release, these methods have some intrinsic problems. Most experiments which have been conducted using them cannot distinguish the effect of synchronization from that caused by different characteristics of individual feedstuffs. Changing feeding frequency or pattern was thus employed in some synchronization experiments to minimize effects of feedstuffs. Because these methods use the same ingredients and alter feeding pattern only, any change in metabolite patterns in the rumen will be mainly due to nutrient synchronization. Richardson et al. (2003) reported that the use of different ingredients may alter microbial or tissue metabolism due to some aspects other than a pattern of dietary nutrient supply. The effects of dietary synchrony were assessed by altering the sequence of feeding individual ingredients by Kaswari et al. (2007), who studied synchrony effects by using different feeding frequency and pattern. For instance, the diets offered had three different sequences to modulate SI (FS-A: energy and protein source together, FS-B: energy source first followed by protein source, FS-C: protein source first followed by energy source).

EFFECTS OF SYNCHRONY BETWEEN ENERGY AND N SUPPLY IN THE RUMEN

Microbial protein synthesis and N retention

Ruminal microorganisms ferment dietary carbohydrates and protein to obtain energy and N for maintenance and growth. Through this process, the two major nutrients (i.e. VFA and microbial protein) for the host animal are produced. MPS is important in ruminants because microbial protein synthesized in the rumen provides from 50% to nearly all amino acids required by ruminants, depending on the rumen undegraded protein (RUP) concentration of the diet (NRC, 2000). MPS is influenced by many dietary and animal factors, which include nitrogen concentrations, nitrogen sources, rates of nitrogen and carbohydrate degradation, carbohydrate in the diets, dry matter intake, and synchronization of nitrogen and energy (Karsli and Russell, 2002). Satter et al. (1977) and Hume et al. (1970) suggested 11-13% CP in diets was adequate to obtain optimal microbial protein synthesis, and Ludden et al. (1995) reported that the amount and degradation rate of RDP were critical for microbial growth in the rumen because this fraction provides the N necessary for microbial growth, even though a low level of CP is provided in the diet.

Dietary protein is composed of RDP and RUP (NRC, 2001). RDP is degraded to peptides and amino acids and further deaminated into ammonia. When dietary RDP is in excess of the amount required by ruminal microorganisms, the excessive RDP is degraded to ammonia N, absorbed, metabolized to urea in the liver, and lost in the urine (Leng and Nolan, 1984). Leng and Nolan (1984) suggested that N metabolism in the rumen can be divided into two distinct events: protein degradation, which provides N sources for rumen microbes, and MPS.

Rumen microorganisms use carbohydrates as the main energy sources although protein also can be used. When adequate energy sources are supplied in the rumen, ammonia N can be converted to microbial protein. If the rate of protein degradation exceeds that of carbohydrate fermentation, large quantities of N are converted into ammonia, and likewise, when the rate of carbohydrate fermentation exceeds that of protein degradation, inefficient microbial protein synthesis may occur (Bach et al., 2005). Therefore, nutrient synchrony between the supply of energy and N to the rumen microorganisms should improve the efficiency of rumen microbes in capturing N and use of energy for microbial growth.

Although it is theoretically plausible that the synchrony of N and energy supply to the rumen microbes increases MPS, experimental evidence is somewhat controversial (Table 1). Some experiments showed positive effects of synchronization. Rotger et al. (2006) used combinations of two nonstructural carbohydrate sources (barley and corn) and two protein sources (soy bean meal and sunflower meal) in their experiment. The fast synchronous diet (barley and sunflower meal) and slow synchronous diet (corn and soybean meal) tended to result in greater microbial N production *in vitro*. Witt et al. (1999b) reported that synchronous treatments having rapidly degradable OM sources produced higher purine derivatives and thus efficiencies of MPS were higher. However, another study conducted by the same group (Witt et al., 1999a) did not show MPS improvement. Using the changing feed ingredient strategy, Herrera-Saldana et al. (1990) reported that a rapid synchronization (both high degradable energy and protein sources) diet showed higher microbial N flow and efficiency of microbial protein synthesis than an asynchronous diet. Rotger et al. (2006) also conducted a similar experiment and indicated that synchronization tended to result in greater microbial N production *in vitro*. Kim et al. (1999a) infused maltodextrin directly to the rumen through a ruminal cannula and showed that synchronous treatments had a positive effect on MPS.

In our previous study, synchrony of energy and nitrogen supply using SI increased MPS in steers (unpublished data). Although there was no difference in DM digestibility, steers on the diet having the highest SI (0.83) excreted more purine derivatives in urine than those on the lowest SI (0.77), which implied that a synchronized diet improved MPS in the rumen. Steers receiving the lowest SI diet had significantly ($p<0.05$) lower total VFA concentration in the rumen, which also indicated a decrease in efficiency of rumen fermentation with diets having lower SI.

There are also some studies that indicated no effect of nutrient synchrony on efficiency of microbial growth.

Table 1. Effects of synchronization on MPS and N retention in the rumen using different methods of nutrient synchrony

Author	Methods for synchronization	Findings
Positive response		
Herra-saldana et al. (1990)	Changing feed ingredients	Rapid synchronization (high degradable energy and protein sources in the rumen) showed highest microbial nitrogen (MN) flows and efficiency of microbial protein synthesis (EMPS) than asynchronous or slow fermentation synchronous diets.
Henning et al. (1991)	Changing feeding pattern and infusion of glucose	Synchronization treatment lowered rumen ammonia concentrations and fluctuation, but no improvement in EMPS or microbial DM production. Glucose pulse dosing improved both microbial DM production and EMPS.
Aldrich et al. (1993)	Changing feed ingredients	Synchronization of rumen available carbohydrate and protein for rapid degradation gave the highest microbial protein flows.
Henning et al. (1993)	Infusion or pulse dosing of sugar and urea/casein	Synchronous treatment had lower N concentrations but did not show improvement in MN flow or EMPS. Continuous sugar infusion resulted in an improvement of MN flow.
Sinclair et al. (1993)	Using synchrony index	Synchronous diet increased microbial N contents and EMPS.
Lee et al. (1997)	Changing feed ingredients	Synchronization of energy and nitrogen release in the rumen increased MPS.
Kolver et al. (1998)	Changing feeding frequency (± timed concentrate feeding)	Synchronization between energy and N release decreased ammonia concentration in the rumen.
Witt et al. (1999b)	Using synchrony index and adjusting synchronicity rate with feed intake restriction	Fast degradation rate of OM and synchronous treatment had the highest production of microbial N, but there was no effect on N retention.
Elseed (2005)	Supplementation of protein source and adjusting feeding frequency	Supplementation of protein sources improved microbial N yield of ammoniated straw and N retention.
Rotger et al. (2006)	Changing feed ingredients	Synchronization tended to result in greater microbial N flow *in vitro*.
No difference or negative response		
Newbold and Rust (1992)	Changing feeding pattern	Asynchronous treatment of energy and N release had little effect on microbial growth.
Henderson et al. (1998)	Changing feed ingredients	Asynchronous diets had more microbial protein flow and EMPS than synchronous diets.
Kim et al. (1999a)	Infusion or pulse dosing of maltodextrin at different times	Continuous maltodextrin infusion showed MPS improvement.
Kim et al. (1999b)	Infusion or pulse dosing of sucrose at different times	Both synchronization and asynchronization condition showed no effect on MPS.
Richardson et al. (2003)	Using synchrony index and changing feeding pattern	There was no significant effect of synchrony treatment on N deposition.
Valkeners et al. (2004)	Using OEB (Dutch protein evaluation system) index	Microbial N flow at the duodenum and N retention were not affected by imbalanced supply of energy and N.
Kaswari et al. (2007)	Changing feeding frequency and feeding pattern	EMPS and non ammonia N flow at the duodenum was the highest in FS-B where energy sources were fed at the first feeding time.
Ichinohe and Fujihara (2008)	Changing feed ingredients and varied to experiment period	Microbial N supply was greater for asynchronous diet than for synchronous diet. N retention was not influenced.

Ichinohe and Fujihara (2008) reported that microbial N supply was greater for an asynchronous diet than a synchronous diet. Kaswari et al. (2007) and Richardson et al. (2003) also showed that there were no differences in efficiencies of MPS and N deposition among treatments in which diets were formulated to have different SI. In Kaswari's experiment, feeding energy sources first improved microbial activity although the synchrony index was low. When the OEB system was used to regulate synchronicity in feeds, duration of imbalance between energy and N supplies for the ruminal microbes had no significant effect on microbial N flows at the duodenum

(Valkeners et al., 2004).

Animal performance and rumen fermentation

Since nutrient synchrony may improve rumen fermentation, increase VFA production and provide more amino acids to the host animal, its effect on animal performance and rumen fermentation were also investigated in many studies (Table 2). Richardson et al. (2003) shifted specific ingredients between morning and evening feeding to provide either a synchronous, intermediate, or asynchronous supply of OM and N to the rumen. The daily live weight gain was not influenced by treatments, but lambs fed an asynchronous diet tended to have a lower fat content in the carcass, which suggested that dietary synchrony improved energy utilization. Witt et al. (1999b) reported that animals given synchronous diets had a significantly higher live weight gain. In the following study using lactating ewes, synchronous treatment tended to increase milk protein yield (g/d), but milk or milk fat yield (g/d) was not improved by the same treatment (Witt et al., 2000). Nutrient supplementation to promote synchronization also showed a positive effect. Elseed (2005) showed that digestibility and VFA production of ammoniated straw were improved by supplying protein, which was explained by the fact that carbohydrate degradation rate of straw could be better matched by supplementation of proteins.

On the contrary, there were some studies which showed no effect of synchronization of energy and N supply in the rumen on animal performance. Rotger et al. (2006) showed that a synchronous feed which had increased OM digestibility and VFA production *in vitro* had no effect on dry matter intake, apparent total digestibility and total VFA production *in vivo*. Shabi et al. (1998) also suggested that synchronization had no effects on ruminal ammonia N and VFA concentration. Cole et al. (2008) conducted meta-analysis of the synchronization effects on DMI, ADG and MPS, calculating synchrony index of the diets used in many studies based on NRC (2000) tabular values for ingredient composition, degradabilities of carbohydrate and CP fraction. They concluded that synchronization of the fermentation of dietary carbohydrates and CP was not as

Table 2. Effects of synchronization on animal performance and rumen fermentation

Author	Methods of synchronization	Findings
Positive response		
Sinclair et al. (1993)	Using synchrony index	Rumen VFA proportions were more stable for synchronous diet than the asynchronous diet, and it was suggested that the synchronized diet caused a more stable microbial population in the rumen, because variation in VFA resulted from change in rumen microbial population.
Witt et al. (1999a)	Using synchrony index and adjusting synchronicity rate. Feeds were given *ad libitum*.	Fast degradation rate of OM and synchronous treatment improved growth efficiency. Total VFA concentrations were not influenced by synchronicity.
Witt et al. (1999b)	Using synchrony index and adjusting synchronicity rate. Feed intake was restricted.	Synchronous treatments with fast or slow degradation rate of OM produced higher live weight gain and feed conversion efficiency than asynchronous diets.
Elseed (2005)	Supplementation of protein source and adjusting feeding frequency	Supplementation of protein sources improved ruminal digestibility of low quality rice straw and rumen fermentation end products in sheep.
Rotger et al. (2006)	Changing feed ingredients	Synchronization tended to result in greater true OM digestibility and VFA concentration *in vitro*.
No difference or negative response		
Shabi et al. (1998)	Changing feed ingredients and adjusting feeding frequency	Synchronization had no effects on ruminal ammonia N and VFA concentration.
Witt et al. (2000)	Using synchrony index	Synchronous diet did not significantly alter milk or milk fat yield while protein yield tended to be increased. There was no significant difference in average rumen VFA concentration and proportion.
Richardson et al. (2003)	Using synchrony index and changing feeding pattern	Live weight gain or feed conversion efficiency were not different, but asynchronous diet resulted in a lower efficiency of dietary energy use.
Kaswari et al. (2007)	Changing feeding frequency and feeding pattern	Ruminal pH, ammonia N and total VFA were not influenced by SI.
Ichinohe et al. (2008)	Changing feed ingredients and varied to experiment period	There were no differences among treatments in DMI and BW change

effective as had been expected and other physiological mechanisms worked in concert to compensate for nutrient asynchrony in a diet (Cole et al., 2008).

Theoretically, synchronization of energy and N supply in the rumen should allow more efficient use of nutrients by rumen microbes, increase microbial protein and fermentation end products, increase available nutrients in the small intestine, and thus potentially improve animal performance and reduce N excretion to the environment. However, due to additional challenges to nutrient synchrony that should be considered, a number of studies showed contradictory results in MPS, N retention and animal production performance.

Feed characteristics are important factors for determining the effect of synchronization. In forage- fed cows, chemical composition of forage could be a challenge to nutrient synchrony. High quality forages may not successfully support nutrient synchrony as indicated by Hersom (2008) since they contain an excessive amount of N compared to energy. Kaswari et al. (2007) reported that accurate evaluation of nutrient synchrony in feedstuffs may be influenced by variation in the *in situ* technique. This includes preparation of samples, characteristics of bags, procedure and locality of incubation, washing, drying, animals, feeding of animals, and degree of correction for small particles lost through the bag pores without being degraded (Madsen and Hvelplund, 1994).

N recycling in the rumen can reduce N deficiency in the rumen. Holder et al. (1995) reported that N recycling was greater with asynchronous diets. N recycling in the rumen plays a major role in regulating the amount of ruminally available N and allows for continuous synchronization of N and energy yielding substrates for the microorganisms in the rumen (Valkeners et al., 2004).

Finally, most rumen bacteria can use ammonia N as a source for microbial growth; however, other nutrients (i.e., preformed amino acids, sulfur, phosphorus, and other minerals and vitamins) are also required for MPS (Sniffen et al., 1987). Therefore, to maximize microbial growth, synchronous supply of not only N and energy but also other nutrients should be considered.

CONCLUSIONS

Nutrient synchrony may have positive roles in maximizing MPS, improving animal performance and reducing N excretion. However, a number of studies showed inconsistent results. It suggests that the nutrient synchrony concept needs further investigation before applying to the field situation. Furthermore, better understanding of the complex ruminal ecosystem of mixed microorganisms and physiological effects such as N recycling is also required.

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