Phosphorus Utilization in Ruminants: Postprint

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Abstract

Phosphorus is an essential element involved in numerous biological reactions in animal organisms. However, environmental issues such as water pollution resulting from phosphorus excretion in livestock and poultry farming, particularly in ruminant production, have become a focal point of industry concern. Consequently, improving phosphorus utilization efficiency and reducing phosphorus excretion represent urgent challenges facing the industry. This paper summarizes research progress on phosphorus utilization in ruminant animals, outlines measures to enhance phosphorus utilization efficiency based on their metabolic characteristics, and proposes directions for future research.

Full Text

Phosphorus Utilization in Ruminants

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Abstract: Phosphorus is an essential macro-mineral element that participates in numerous biological processes within animal organisms. However, environmental issues arising from phosphorus excretion in livestock farming, particularly from ruminant operations, have become a major industry concern, with water pollution being especially problematic. Consequently, improving phosphorus utilization efficiency while reducing phosphorus emissions represents an urgent challenge for the sector. This review synthesizes current research progress on phosphorus utilization in ruminants, summarizes measures to enhance phosphorus use efficiency based on ruminant metabolic characteristics, and proposes directions for future research.

Keywords: ruminant; phytate phosphorus; performance; digestibility; phosphorus utilization efficiency

Phosphorus constitutes one of the essential macro-mineral elements in animal organisms, playing vital roles in bone development, intracellular energy transfer, blood acid-base balance, and enzymatic reactions. In ruminants, phosphorus fulfills more critical biological functions within both the animal body and rumen microbiota than other minerals. Insufficient phosphorus intake disrupts normal metabolism, impairing reproductive and productive performance, while excessive phosphorus supplementation not only wastes mineral resources but also causes environmental problems such as soil and water eutrophication, resulting in economic losses and increased burdens for producers. Livestock excrete substantial phosphorus through feces; for instance, 58% of phosphorus intake is eliminated via feces in lactating dairy cows [1]. In the United States, livestock operations contribute 33% of phosphorus entering water bodies [2], with ruminants accounting for approximately 60% of total phosphorus excretion from livestock farming [3]. As national regulations increasingly strengthen pollution control and strictly limit manure discharge, and given that global mineral phosphorus resources may become scarce and expensive [4], the industry must urgently address how to reduce dietary phosphorus supplementation while maintaining normal productive performance, improve phosphorus utilization efficiency in ruminants, and minimize phosphorus excretion. This review primarily summarizes phosphorus digestion and metabolism characteristics, requirements, and effects on productive performance in ruminants, and discusses strategies for improving phosphorus utilization to guide phosphorus reduction efforts in production practice.

1 Digestion and Metabolism Characteristics of Phosphorus

Total phosphorus entering the digestive tract comprises two components: endogenous and exogenous phosphorus. The exogenous portion originates from the diet, while the endogenous portion primarily comes from saliva. Ruminants exhibit low absorption rates of phosphate ions in the forestomach, with phosphorus absorption occurring mainly in the anterior small intestine. Unlike monogastric animals, which utilize both vitamin D-dependent active transport and passive absorption for phosphorus uptake in the small intestine, the primary absorption mechanism in ruminants remains unclear. Carrier-mediated transport may reduce phosphorus absorption efficiency at high concentrations [5], potentially explaining why phosphorus supplementation decreases utilization efficiency. Numerous nutritional factors affect phosphorus utilization, including dietary phosphorus content, total phosphorus level, phosphorus source, forage-to-grain ratio, and dietary calcium content. Animal age, physiological stage, and endocrine hormones also influence phosphorus digestion and metabolism. Researchers have employed metabolic models to predict phosphorus absorption and excretion; for example, Hill et al. [6] developed a dynamic model of phosphorus digestion in lactating dairy cows assuming a phosphorus intake of 75 g/d, with total tract digestibility of 38%, 65% recycled into the rumen via saliva, and 30% utilized for milk synthesis. Phytate phosphorus digestibility in the rumen reached 74%, but no absorption occurred in the posterior digestive tract, while inorganic and organic phosphorus digestibility in the posterior tract was 48% and 89%, respectively. Common indicators for dietary available phosphorus include apparent phosphorus digestibility and relative biological value, though only true phosphorus digestibility accurately reflects absorption and utilization. Current research lacks a standardized evaluation system for effective phosphorus utilization, making it difficult to unify and quantify the effects of different factors. Research in this area should therefore become a priority, particularly regarding phytate phosphorus, which constitutes a large proportion of ruminant diets and shows potential for reducing phosphorus excretion.

1.1 Intraruminal Digestion of Phytate Phosphorus

While phytase is widely used as a feed additive in monogastric animals, ruminants can effectively utilize dietary phytate phosphorus because rumen microorganisms produce phytase. Phytic acid (myo-inositol hexakisphosphate, IP-6) represents the primary storage form of phosphorus in cereal grains and their by-products, comprising a high proportion of total phosphorus in ruminant diets. Under the action of microbial phytase synthesized in the rumen, phytic acid hydrolyzes into lower phosphorylated inositols [inositol monophosphate (IP-1), inositol diphosphate (IP-2), inositol triphosphate (IP-3), inositol tetraphosphate (IP-4), inositol pentaphosphate (IP-5)] and phosphate groups, which are further digested and absorbed in the small intestine. Ray et al. [7] measured phytate excretion in feces and found that dairy cows digest phytate at remarkably high rates of 93–99%. Supplemental phytate phosphorus did not affect its hydrolysis in the rumen, indicating that increased phytate intake does not saturate ruminal phytase activity. The study also demonstrated that phosphorus source had no significant effect on net inorganic phosphorus digestion or phytate phosphorus digestibility in the large intestine, suggesting that changes in total phosphorus content influence phosphorus excretion more than dietary phosphorus source differences.

Phytate hydrolysis characteristics vary among different feed ingredients [8], as does their ability to bind with proteins and other nutrients, likely due to differences in phytate storage forms and locations within plant seeds [9]. In oilseeds, phytate primarily resides in the aleurone layer, while in soybeans and corn it is located in protein bodies and germ, respectively. Consequently, oilseeds and cereal by-products generally contain high phytate phosphorus levels, whereas forages contain low phytate levels, existing only in alfalfa and some grasses. Feed processing methods such as heat treatment and formaldehyde treatment, along with dietary composition, affect phytate digestion and utilization. Increasing dietary phytate content promotes its degradation in the rumen and total digestive tract of dairy cows, whereas phosphorus supplementation produces the opposite effect [10], consistent with Haese et al.' s [11] in vitro findings. Haese et al. [11] also observed significant differences in phytate degradability among feed ingredients; although high phytate content improved ruminal digestibility, oilseed meals, particularly rapeseed meal, showed lower degradation rates than cereal ingredients. Therefore, when diets contain oilseed meals, increasing phytate content can promote ruminal degradation, especially for high-producing dairy cows where increased dry matter intake (DMI) reduces rumen retention time and suboptimal fermentation conditions limit phytate degradation [12]. Dietary composition also affects ruminal phytase activity [11], necessitating further research on characteristics of different microorganisms and their phytase production.

NRC (2001) specified phosphorus digestibility values of 64% and 70% for forages and concentrates, respectively. Cherry et al. [13] used the mobile nylon bag technique to measure phosphorus degradation from forages in Holstein steers, reporting total tract phosphorus digestibility of 90.6%, 93.7%, and 83.8% for corn silage, alfalfa hay, and bermudagrass hay, respectively. Forage maturity stage significantly affects phosphorus degradation; for example, phosphorus total tract digestibility decreased by 5.4% in forages harvested 35 days after first cutting compared to 14 days [14]. Wu [15] further demonstrated that replacing alfalfa hay with soybean hulls reduced phosphorus excretion by improving phosphorus digestibility without affecting dairy cow performance, indicating that using highly digestible fiber sources can lower dietary phosphorus content while meeting requirements, thereby reducing phosphorus excretion.

These findings suggest that precise knowledge of phosphorus release from different feed ingredients throughout the digestive tract is essential, and their phosphorus digestibility should be fully considered during diet formulation.

1.2 Postruminal Digestion of Phytate Phosphorus

Further hydrolysis of phytate passing through the rumen can occur, though research in this area remains limited. Both monogastric animals and ruminants primarily absorb phosphorus in the small intestine [16]; however, phytate phosphorus digestibility in the small intestine of dairy cows is low [17]. Chopped forage affects phosphorus flow and absorption, increasing phosphorus passage through the small intestine and consequently phosphorus excretion [12]. Riojas-McCollister et al. [14] observed significant phosphorus release from forages like alfalfa in the postruminal digestive tract. The primary degradation sites for phosphorus from different ingredients may vary. Cherry et al. [13] found substantial differences in phosphorus degradation from feed ingredients across digestive tract segments, with some legume forages showing primary digestion in the intestine, possibly due to condensed tannins that bind phosphorus and slow ruminal degradation. Large intestinal microorganisms can also produce phytase to catalyze limited phytate hydrolysis. Ray et al. [7] observed phosphorus absorption in the large intestine, with 16% of phytate flowing from the ileum degraded in the large intestine, unaffected by dietary phytate content. Rumen and large intestinal microbial phytases may have different substrate preferences, potentially compensating for insufficient phytate degradation and phosphorus absorption in the anterior intestine. Further research is needed on phytate degradation sites and their digestion and absorption in the large intestine.

Comparing studies to identify factors affecting phytate degradation is challenging due to variations in DMI, dietary composition, sampling, and analytical methods. Moreover, factors observed in vitro may not apply in vivo. Current research primarily lacks a standardized evaluation system for effective phosphorus utilization. Future studies should focus on: (1) quantitatively describing phosphorus absorption in the digestive tract and endogenous phosphorus secretion to improve dynamic models of phosphorus digestion and metabolism; (2) investigating phosphorus degradation characteristics of different feed ingredients to obtain true digestibility data for diet formulation; and (3) exploring effects of microbial flora on production of different phytase types and phytate phosphorus digestion, along with determining optimal phosphorus levels for rumen microorganisms under these conditions.

2 Phosphorus Requirements of Ruminants

NRC (2001) recommends dietary phosphorus concentrations of 3.20–3.80 g/kg DM for dairy cows producing 25–55 kg of milk, with a phosphorus requirement of 3.2 g per kg of milk containing 4.5% fat. Liu [18] reported that these recommendations are adequate for lactating dairy cows, with direct measurement of milk phosphorus content yielding a lactation requirement of 0.9 g/kg milk. Phosphorus concentrations exceeding 3.8 g/kg DM showed no significant effects on reproductive or productive performance. Although some studies indicate that feeding phosphorus above NRC (2001) recommendations does not affect performance [19], actual feeding levels still exceed NRC (2001) by 30% [20], indicating widespread over-supplementation in practice. Geisert et al. [21] found that feeding heifers diets containing 0.10% phosphorus caused deficiency, while the optimal requirement ranged from 0.10% to 0.17%, with this range also reducing phosphorus excretion, making phosphorus supplementation unnecessary in grain-based diets.

Bjelland et al. [22] suggested that dietary phosphorus concentrations of 0.20%–0.35% meet the nutritional needs of replacement dairy heifers, while Kebreab et al. [23] identified excessive phosphorus feeding as the primary cause of environmental phosphorus pollution from dairy operations. China' s "Feeding Standard for Meat Sheep" (NY/T 816—2004) recommends 0.35% dietary phosphorus for growing goats, while Wang et al. [24] demonstrated that 0.29%–0.41% dietary phosphorus meets the nutritional requirements of Laoshan dairy goats, with 0.59% phosphorus increasing excretion and reducing apparent phosphorus digestibility.

Most studies recommend moderately reducing dietary phosphorus concentrations in ruminants, though current optimal supplementation levels are based on indicators such as reproductive performance, milk yield, and bone stability

[25]. Reducing dietary phosphorus to decrease fecal phosphorus excretion is currently encouraged. Macrae et al. [26] observed hypophosphatemia in over 10% of early-lactation cows, possibly resulting from increased phosphorus requirements due to lactation or higher milk production, combined with low prepartum dietary phosphorus or minimal feed intake during early lactation. Knowlton et al. [27] similarly suggested that early-lactation cows fed low-phosphorus diets must mobilize bone phosphorus to meet maintenance and production needs. However, Eisenberg et al. [28] found that feeding low-phosphorus diets (0.2%) did not compromise dairy cow health by impairing intracellular immune function. Therefore, research on ruminant phosphorus requirements should examine metabolic aspects beyond reproductive and productive performance.

3 Effects of Phosphorus Content on Performance, Nutrient Digestibility, and Phosphorus Excretion

Total phosphorus intake is generally considered the primary determinant of phosphorus excretion in dairy cows, with many studies confirming a positive correlation [29]. Feeding low-phosphorus diets can significantly reduce phosphorus excretion [30]. Intestinal phosphorus absorption and bone phosphorus deposition/resorption constitute the main regulatory mechanisms maintaining appropriate blood phosphorus levels, with bone phosphorus balance related to phosphorus intake and ruminal phytase activity. Therefore, reducing phosphorus intake below recommended levels may not necessarily improve phytate phosphorus utilization. Dietary phosphorus concentration does not affect apparent DM digestibility in lactating dairy cows, with apparent phosphorus digestibility ranging from 36.61% to 38.76% [31]. Zhao et al. [32] found that 0.32% dietary phosphorus did not affect Holstein dairy cow performance, though apparent phosphorus digestibility decreased significantly with increasing phosphorus intake. Reducing dietary phosphorus concentration also significantly decreased phosphorus excretion [33] and significantly affected apparent digestibility of neutral detergent fiber and acid detergent fiber [34]. Under heat stress conditions, Holstein dairy cows fed 0.29% dietary phosphorus showed significantly lower milk yield and milk fat percentage compared to those fed 0.35% and 0.42% phosphorus, with calcium and phosphorus metabolism also affected [35]. Puggaard et al. [36] similarly observed that reducing dietary phosphorus from 3.4 to 2.3 g/kg DM significantly decreased DMI, milk yield, and milk protein production in early-lactation dairy cows.

In summary, numerous studies on ruminant phosphorus requirements, relationships between dietary phosphorus and nutrient digestibility, and effects of dietary phosphorus on performance generally support moderate reductions in dietary phosphorus. However, inconsistent results across studies may stem from different phosphorus sources—for example, both dicalcium phosphate and wheat bran can rapidly increase dietary phosphorus, yet their differential effects on experimental outcomes are often overlooked. Beyond factors like experimental animals and diets, the primary issue is the lack of a standardized effective phosphorus evaluation system. Apparent phosphorus digestibility and relative biological value cannot reflect true phosphorus absorption and utilization, and the absence of accurate assessment of effective phosphorus in feed ingredients represents the fundamental cause of excessive phosphorus excretion, warranting primary focus in future research.

4.1 Supplementation of Exogenous Phytase

Endogenous plant phytase plays a minor role in phytate degradation in the rumen, making it impractical to promote phytate hydrolysis by increasing the proportion of concentrate containing high endogenous phytase [11]. Exogenous phytase, a widely used feed additive for monogastric animals derived from bacteria, yeast, *Aspergillus niger*, and other microorganisms [37], has few commercial applications for ruminants. Knowlton et al. [38] found that supplementing lactating dairy cows with exogenous phytase reduced fecal phosphorus excretion. Although Jarrett et al. [12] observed contrary results, their study showed that phytase increased phytate phosphorus digestibility from 96.7% to 97.6% and rapidly degraded phytate phosphorus to inorganic phosphorus in total mixed rations (TMR). Kincaid et al. [39] increased total tract phytate phosphorus digestibility from 80% to 85% by supplementing dairy cows with phytase. These results suggest that phytase supplementation may promote phytate phosphorus degradation while reducing total dietary phosphorus, thereby improving phosphorus digestibility and reducing excretion, though the effectiveness of exogenous phytase in ruminants requires further investigation.

4.2 Optimization of Feed Processing Technology

As previously discussed, phytate digestibility depends on its storage form and distribution in plant feedstuffs, with phytate primarily located in the aleurone layer and outer bran. Mechanical processing to separate these components can effectively reduce phytate phosphorus content [40], though grinding and other methods may cause nutrient losses, and ruminant diets already contain cereal by-products. Fermentation effectively degrades phytate phosphorus [41] because lactic acid bacteria and yeast produce phytase [42], and microbial acid production lowers feed pH, facilitating endogenous plant phytase activity [43]. Heat treatment and chemical agents like formaldehyde reduce ruminal solubility, but lactic acid treatment of barley enhances starch and fiber digestion while catalyzing phytate hydrolysis and promoting phosphorus digestion. Barley treated with organic acids like lactic and citric acid also improves ruminant NDF digestion, possibly through effects on rumen bacterial flora. Germination rapidly reduces phytate content while increasing phytase activity [44], though effects of sprouted grains on growth and performance in ruminants require further study. Additionally, soaking can remove phytate by exploiting its water solubility, with soaking conditions also favoring increased phytase activity for effective phytate degradation, though this process may cause losses of other nutrients. These methods can reduce phytate content and enhance phytase activity to varying degrees, but their effects on digestion of other nutrients must be considered comprehensively.

4.3 Optimization of Dietary Formulation

Phosphorus homeostasis is primarily regulated through salivary phosphorus recycling and endogenous phosphorus excretion, both closely related to phosphorus absorption in ruminants [45]. Calcium and phosphorus promote growth, maintain normal immune function, and improve productive performance [46]. Earlier research suggested optimal calcium-to-phosphorus ratios of 1–7:1. However, calcium binds with phytate in the rumen to form poorly available calcium phytate, inhibiting phytase hydrolysis and reducing calcium utilization. Excess calcium and other metal ions such as iron, magnesium, and aluminum can combine with phosphate to form insoluble salts that hinder phosphorus absorption. Ruminants lack mechanisms to excrete excess calcium, and dietary calcium levels tend to be high, making appropriate calcium-to-phosphorus ratios and calcium concentrations crucial for phosphorus utilization. Vitamin D is an important factor for maintaining extracellular fluid phosphorus homeostasis; 1,25-dihydroxyvitamin D promotes intestinal phosphorus absorption, and its production is stimulated when plasma phosphorus is low. Active transport of low phosphorus concentrations also depends on vitamin D, making vitamin D supplementation particularly important when formulating low-phosphorus diets. Additionally, as previously mentioned, the availability of phosphorus from concentrate ingredients requires careful consideration, though this necessitates fundamental research support.

5 Summary

Overall, current production practices can effectively reduce phosphorus excretion by moderately decreasing actual phosphorus supplementation levels in ruminant diets. However, research on the true availability of phosphorus from different feed ingredients remains limited, and standardized methods for evaluating phosphorus digestibility need establishment to enable effective comparison of study results, optimize dynamic models of phosphorus digestion and metabolism, and balance various factors in diet formulation to improve phosphorus digestibility.

References

[1] ALVAREZ-FUENTES G, APPUHAMY J A D R N, KEBREAB E. Prediction of phosphorus output in manure and milk lactating dairy cows[J]. Journal of Dairy Science, 2016, 99(1): 771–782.

[2] FAO. Livestock’ s long shadow: environmental issues and options[M]. [S.l.]: Food and Agriculture Organization of the United Nations FAO, 2006.

[3] TAMMINGA S. Nutrition management of dairy cows as a contribution to pollution control[J]. Journal of Dairy Science, 1992, 75(1): 345-357.

[4] CORDELL D, DRANGERT J O, WHITE S. The story of phosphorus: global food security and food for thought[J]. Global Environmental Change, 2009, 19(2): 292-305.

[5] 曹满湖. 日粮磷水平和 VD3 对 Na+/Pi- b mRNA 表达和磷吸收的影响 [D]. 博士学位论文. 长沙: 湖南农业大学, 2010.

[6] HILL S R, KNOWLTON K F, KEBREAB E, et al. A model of phosphorus digestion and metabolism in the lactating dairy cow[J]. Journal of Dairy Science, 2008, 91(5): 2021-2032.

[7] RAY P P, JARRETT J, KNOWLTON K F. Effect of dietary phytate on phosphorus digestibility in dairy cows[J]. Journal of Dairy Science, 2013, 96(2): 1156-1163.

[8] BRASK-PEDERSEN D N, GLITSØ L V, SKOV L K, et al. Effect of exogenous phytase on feed inositol phosphate hydrolysis in an in vitro rumen fluid buffer system[J]. Journal of Dairy Science, 2011, 94(2): 951-959.

[9] HAESE E, LENGOWSKI M, GRÄTER E, et al. Ruminal phytate degradation of maize grain and rapeseed meal in vitro and as affected by phytate content in donor animal diets and inorganic phosphorus buffer[J]. Journal Animal Physiology Animal Nutrition, 2017, 101(5): 868-880.

[10] HAESE E, MÜLLER K, STEINGASS H, et al. Effects of mineral and rapeseed phosphorus supplementation phytate degradation dairy cows[J]. Archives of Animal Nutrition, 2014, 68(6): 478-491.

[11] HAESE E, MÖHRING J, STEINGASS H, et al. Effect of dietary mineral phosphorus and phytate on in situ ruminal phytate disappearance from different concentrates in dairy cows[J]. Journal of Dairy Science, 2017, 100(5): 3672-3684.

[12] JARRETT J P, WILSON J W, RAY P P, et al. The effects of forage particle length and exogenous phytase inclusion on phosphorus digestion and absorption in lactating cows[J]. Journal of Dairy Science, 2014, 97(1): 411-418.

[13] CHERRY N M, LAMBERT B D, MUIR J P. Ruminal and total tract phosphorus release from feedstuffs in cattle measured using the mobile nylon bag technique[J]. Journal of Animal Physiology and Animal Nutrition, 2010, 94(5): 665-669.

[14] RIOJAS-MCCOLLISTER A V, LAMBERT B D, MUIR J P. Maturity of coastal bermudagrass and alfalfa affects ruminal in situ and total tract dry matter and phosphorus disappearance cannulated steers[J]. Journal of Animal Physiology and Animal Nutrition, 2011, 95(2): 267-272.

[15] WU Z. Utilization of phosphorus in lactating cows fed varying amounts of phosphorus and sources of fiber[J]. Journal of Dairy Science, 2005, 88(8): 2850-2859.

[16] FENG X, RONK E, HANIGAN M D, et al. Effect of dietary phosphorus on intestinal phosphorus absorption growing Holstein steers[J]. Journal Dairy Science, 2015, 98(5): 3410-3416.

[17] BRASK-PEDERSEN D N, GLITSØ L V, SKOV L K, et al. Effect of exogenous phytase on degradation inositol phosphate dairy cows[J]. Journal Dairy Science, 2013, 96(3): 1691-1700.

[18] Harland. 反刍动物磷需要量的重估环境保护要求饲喂给奶牛低于推荐量的低磷日粮 [J]. 刘春生, 译. 中国奶牛, 2004(1): 31-33.

[19] REID M, O'DONOVAN M, ELLIOTT C T, et al. The effect of dietary crude protein and phosphorus on grass-fed dairy cow production, nutrient status, and milk heat stability[J]. Journal of Dairy Science, 2015, 98(1): 517-531.

[20] DOU Z, FERGUSON J D, FIORINI J, et al. Phosphorus feeding levels and critical control points on dairy farms[J]. Journal of Dairy Science, 2003, 86(11): 3787-3795.

[21] GEISERT B G, ERICKSON G E, KLOPFENSTEIN T J, et al. Phosphorus requirement and excretion of finishing beef cattle fed different concentrations of phosphorus[J]. Journal of Animal Science, 2010, 88(7): 2393-2402.

[22] BJELLAND D W, WEIGEL K A, HOFFMAN P C, et al. The effect of feeding dairy heifers diets with and without supplemental phosphorus on growth, reproductive efficiency, health, and lactation performance[J]. Journal of Dairy Science, 2011, 94(12): 6233-6242.

[23] KEBREAB E, HANSEN A V, LEYTEM A B. Feed management practices to reduce manure phosphorus excretion in dairy cattle[J]. Advances in Animal Biosciences, 2013, 4(Suppl.1): 37-41.

[24] 王建华, 戈新, 汪文鑫, 等. 磷在崂山奶山羊体内消化、分配和利用的研究 [J]. 饲料研究, 2007(12): 1-4.

[25] VALK H, ŠEBEK L B J, BEYNEN A C. Influence of phosphorus intake on excretion and blood plasma and saliva concentrations of phosphorus in dairy cows[J]. Journal of Dairy Science, 2002, 85(10): 2642-2649.

[26] MACRAE A I, WHITAKER D A, BURROUGH E, et al. Use of metabolic profiles for the assessment of dietary adequacy in UK dairy herds[J]. Veterinary Record, 2006, 159(20): 655-661.

[27] KNOWLTON K F, HERBEIN J H. Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content[J]. Journal of Dairy Science, 2002, 85(5): 1227-1236.

[28] EISENBERG S W F, RAVESLOOT L, KOETS A P, et al. Influence of feeding a low-phosphorus leucocyte function dairy cows[J]. Journal of Dairy Science, 2014, 97(8): 5176-5184.

[29] EKELUND A, SPÖRNDLY R, VALK H, et al. Effects of varying monosodium phosphate intake phosphorus excretion dairy cows[J]. Livestock Production Science, 2005, 96(2/3): 301-306.

[30] FERRIS C P, MCCOY M A, PATTERSON D C, et al. Effect of offering dairy cows diets differing in phosphorus concentration over four successive lactations: 2. Health, fertility, bone phosphorus reserves and nutrient utilisation[J]. Animal, 2010, 4(4): 560-571.

[31] 张峰, 邱伟, 刘小静, 等. 日粮磷水平对泌乳奶牛生产性能及磷表观消化率的影响 [J]. 天津农业科学, 2013, 19(3): 38-42.

[32] 赵恒聚, 高艳霞, 李秋凤, 等. 日粮磷水平对泌乳奶牛生产性能及磷排放的影响 [J]. 中国农业科学, 2010, 44(22): 4687-4693.

[33] 孙国强, 王书芝, 吕永艳, 等. 饲粮磷含量对 11~15 月龄青年奶牛生长性能、血液指标和磷排泄的影响 [J]. 动物营养学报, 2015, 27(12): 3912-3919.

[34] 许建海, 张微, 黄洁, 等. 饲粮磷水平对西门塔尔杂交后备母牛营养物质表观消化率的影响 [J]. 动物营养学报, 2011, 23(4): 589-596.

[35] 张玉诚, 薛白, 肖俊, 等. 饲粮磷水平对热应激奶牛生产性能和血液指标的影响 [J]. 动物营养学报, 2015, 27(3): 749-755.

[36] PUGGAARD L, LUND P, LIESEGANG A, et al. Long term effect of reduced dietary phosphorus on feed intake and milk yield in dry and lactating dairy cows[J]. Livestock Science, 2014, 159: 18-28.

[37] HUMER E, SCHWARZ C, SCHEDLE K. Phytate in pig and poultry nutrition[J]. Journal of Animal Physiology and Animal Nutrition, 2015, 99(4): 605-625.

[38] KNOWLTON K F, TAYLOR M S, HILL S R, et al. Manure nutrient excretion by lactating cows fed exogenous phytase and cellulase[J]. Journal of Dairy Science, 2007, 90(9): 4356-4360.

[39] KINCAID R L, GARIKIPATI D K, NENNICH T D, et al. Effect of grain source and exogenous phytase phosphorus digestibility dairy cows[J]. Journal of Dairy Science, 2005, 88(8): 2893-2902.

[40] SCHLEMMER U, FRØLICH W, PRIETO R M, et al. Phytate in foods and significance for humans: food sources, intake, processing, bioavailability, protective role and analysis[J]. Molecular Nutrition & Food Research, 2009, 53(Suppl.2): S330-S375.

[41] JAKOBSEN G V, JENSEN B B, BACH KNUDSEN K E, et al. Fermentation and addition of enzymes to a diet based on high-moisture corn, rapeseed cake, and peas improve digestibility of nonstarch polysaccharides, crude protein, and phosphorus pigs[J]. Journal of Animal Science, 2015, 93(5): 2234-2245.

[42] LIU N, RU Y J, WANG J P, et al. Effect of dietary sodium phytate and microbial phytase on lipase activity lipid metabolism of broiler chickens[J]. British

Journal Nutrition, 2010, 103(6): 862-868.

[43] LEENHARDT F, LEVRAT-VERNY M A, CHANLIAUD E, et al. Moderate decrease of pH by sourdough fermentation is sufficient to reduce phytate content of whole wheat flour through endogenous phytase activity[J]. Journal of Agricultural and Food Chemistry, 2005, 53(1): 98-102.

[44] SOKRAB A M, AHMED I A M, BABIKER E E. Effect of fermentation on antinutrients, and total and extractable minerals of high and low phytate corn genotypes[J]. Journal of Food Science and Technology, 2014, 51(10): 2608-2615.

[45] 颜琼娴, 谭支良. 反刍动物内源磷排泄量及磷真消化率的研究进展 [J]. 华北农学报, 2009, 24(增刊): 231-235.

[46] 沈维军, 王加启, 卜登攀, 等. 2008-2009 年反刍动物营养研究进展 . 矿物质元素 [J]. 中国畜牧兽医, 2010, 37(5): 5-9.

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