Iranian Journal of Applied Animal Science

Importance of Phosphorus in Farm Animals

Review Article

S. Manopriya[1], A.A.A.U. Aberathna[1], D.A. Satharasinghe[2], L.J.P.A.P. Jayasooriya[2], M.M.M.G.P.G. Mantilaka[3], C.A.N. Fernando[4], B.P.A. Jayaweera[1], W.A.D.V. Weerathilake[1], G.A. Prathapasinghe[1], J.A. Liyanage[5] and J.M.K.J.K. Premarathne[1*]

[1] Department of Livestock and Avian Science, Faculty of Livestock, Fisheries and Nutrition, Wayamba University of Sri Lanka, Makandura, Gonawila (NWP), 60170, Sri Lanka
[2] Department of Basic Veterinary Science, Faculty of Veterinary Medicine and Animal Science, University of Peradeniya, Peradeniya, 20400, Sri Lanka
[3] Institute of Science, University of Peradeniya, Peradeniya, 20400, Sri Lanka
[4] Department of Nano Science Technology, Faculty of Technology, Wayamba University of Sri Lanka, Kuliyapitiya, 60200, Sri Lanka
[5] Department of Chemistry, Faculty of Science, University of Kelaniya, 11600, Sri Lanka

Received on: 3 Jul 2021
Revised on: 25 Aug 2021
Accepted on: 16 Sep 2021
Online Published on: Jun 2022

*Correspondence E-mail: krissjayaruk@wyb.ac.lk

ABSTRACT

Nutrition is a crucial factor in animal production. Feeding animals with a well-balanced diet is beneficial economically and promotes animal welfare. Mineral supplements are the third most costly component in animal feed. Phosphorus (P) is one of the key minerals responsible for skeletal development, energy metabolism, cell signaling and is a constituent of nucleotides. An animal's P requirement varies with species, production trait, age and management practices. Dietary P should meet the growth, maintenance, and production requirements of animals. Deficiency in dietary P causes severe impacts on skeletal development and growth in young animals and long-term deficiencies can impact both animal welfare and production parameters. Overfeeding of P can lead to nutritional disorders related to Ca metabolism. Therefore, maintaining the balance between Ca and P in the diet is crucial in feeding. Excess P is not retained in the body and excreted with faecal matter. Through the homeostasis process, animals are able to balance the mineral composition in their bodies. The primary P source in the diet comes as organic P from plants and inorganic P from supplements. The bioavailability of the P varies within animals according to physiological and functional variabilities. Understanding the physiology as well as functional and production variabilities in animals is beneficial in managing the economic and environmental aspects of animal husbandry.

KEY WORDS homeostasis, mineral, nutrition, phosphorus.

INTRODUCTION

Phosphorus (P) is a vital mineral that cannot be replaced by any other nutrient in the diet. However, it is a costly mineral supplement and is typically the second or third highest cost component of all dietary supplements, following energy and protein supplements (Satter *et al.* 2005; Moe, 2008). P is an essential component of intermediates in central and energy metabolism, signaling molecules, and structural macromolecules like nucleic acids and phospholipids. Mainly P is involved in carbohydrate metabolism, fat metabolism, amino acid metabolism and serves as a structural component in high energy compounds such as adenosine triphosphate (ATP) and adenosine diphosphate (ADP) (Westerblad *et al.* 2010). It is vital in maintaining the standard blood chemistry, nervous tissue metabolism, transporttation of lipids and fatty acids. Calcium and P are the major structural components of the animal's skeletal system and comprise a 2:1 ratio within the animal's body (Suttle, 2010; Adedokun and Adeola, 2013).

The major dietary P sources for animals are plants and inorganic P. Ruminants can utilize plant-based P sources efficiently, but poultry and other non-ruminants cannot utilize them effectively (Cromwell, 2005; Shastak *et al.* 2012). Moreover, as the main ingredients of a non-ruminant diet mainly constitute of cereal grains and their by-products, the total bioavailable P content in the diet is poor (Garg *et al.* 2014; Bhanderi *et al.* 2016).

Animal-based P sources such as meat and bone meal have relatively high bioavailability compared to plant sources though there were some biosafety issues and legal issues in their use. This policy increases the demand for inorganic feed phosphates (Kiarie and Nyachoti, 2010). Thus, additional P supplements should be added to the feed to full fill the requirement of those animals only fed on plant-based sources. Presently, these additional requirements come from inorganic P sources such as dicalcium phosphate (DCP), monocalcium phosphate (MDP), monocalcium phosphate (MCP), and defluorinated phosphate (MDP and MCP) (Lamp *et al.* 2020).

A significant source of inorganic feed phosphate is derived from rock phosphate, but this natural resource is limited and rapidly dwindling due to continuous demand and P wastage and loss caused by improper handling (Edixhoven *et al.* 2014; USGS, 2021). Excessive dietary P concentrations increase costs and wastage in animal feed as it is excreted in faecal matter, leading to environmental pollution (Li *et al.* 2016). A deeper understanding of P metabolism and specific P requirements in farm animals will help maintain the sustainable use of P in animal husbandry. This study looks at the specific requirements of P in poultry and cattle by focusing on the homeostasis process of P to avoid overfeeding and deficiency (Edixhoven *et al.* 2014; USGS, 2021).

Role of phosphorus in the body

Calcium is the most abundant mineral in the body but phosphorus plays a close second, but significant next to Ca as bones are a major reservoir for body phosphate. In bones, 80% of P is stored in the form of hydroxyapatite $[Ca_{10}(PO_4)_6(OH)_2]$ and the remaining 20% is in the soft tissues and serum phosphate (Pi) (Blaine *et al.* 2014). Pi in serum is in the form of inorganic orthophosphates. Inorganic phosphates can be either dibasic (HPO_4^{2-}) or monobasic ($H_2PO_4^-$). The serum in dibasic form is about 80%, whilst monobasic is around 10%. P circulates in the blood as free ions, bound to Na^+, Mg^{2+}, Ca^{2+} or bound to proteins (10-20% of serum phosphate). Other than this, Pi is bound to organic compounds such as protein, lipid DNA and RNA (Blaine *et al.* 2014).

Blood Pi is an unreliable indicator of body stores since the level can vary due to several factors other than metabolic changes. The age, sex, genetic selection, ambient temperature changes during management and dietary supplementation of nutrients can affect blood Pi levels (Whitehead, 2002; Bar *et al.* 2003). In younger animals, serum Pi is higher in concentration due to the growth hormone effect, increasing P's reabsorption in the kidney. On the other hand, feeding carbohydrates reduces the serum Pi due to increased glycolysis. The animal-based diet increases serum phosphate due to high P content (Lanyon, 2005).

Pi enters the metabolism via non-dedicated pathways, whilst P enters the metabolic pathway mainly through ATP synthesis. ATP is synthesized from ADP with the incorporation of high energy Pi. Pi is transported during glycolysis and in the Krebs cycle, ensuring the transfer of P to other phosphorylated intermediates (Hinkle, 2005). Most of these intermediates are involved in many of the anabolic and catabolic functions of the body. Also, P intermediates in glycolysis provide primary substrate to nucleotide, carbohydrate, protein and lipid synthesis (Boros *et al.* 2002). P is essential for animals' reproductive performance and is necessary to obtain higher production performances (Wu *et al.* 2007; Ibtisham *et al.* 2018).

Role of P in cattle

The P metabolism in ruminants differs from poultry and other mono-gastric animals. Ruminants utilize a large amount of phytic P than non-ruminants due to the presence of microbes in the rumen. Microbial phytase secretion can digest around 90% of phytic P in forage and grain-based diets (Karn, 2001). In addition to the dietary P, intrinsic P from gastric secretions also contributes to meeting ruminants' P requirement. Salivary P act as a crucial buffer in the rumen to enhance microbial digestion (Puggaard *et al.* 2011). In addition, a smaller amount of endogenous Pi, around 30% of the body P requirement (Humer and Zebeli, 2015), is released with gastric, pancreatic juice, bile and intestinal fluid. When dietary P is high, it is absorbed into the small intestine via passive absorption (Singh *et al.* 2018).

The P requirement of the dairy cattle will be estimated based on the requirement for maintenance, milk production, growth, and fetal growth. P requirement for maintenance is related to body weight and dry matter (DM) intake of the animal. In a dairy cow, this is equal to 1g P/kg DM intake plus 0.002 g P/kg bodyweight (Satter *et al.* 2005). P requirement for maintenance can be calculated using the equation developed by the AFRC (1993) given below.

P (g d-1)= (1.2+(4.635×MW0.22)×(BW-0.22)) × WG

Where:
P: P requirement per day.
MW: expected mature live body weight.
BW: current body weight.
WG: weight gain (kg/d).

P requirement for growth of dairy cow is equal to P deposited in the body during growth. In dairy cows, P requirement during the gestation period varies with fetal development. The requirement reaches an optimum level during the last three months of the gestation period (Cavestany *et al.* 2005; Kovacs, 2014). It is estimated that the P requirement on the 190th day of pregnancy is 1.9 g P/day and will increase up to 5.4 g P/day on the 280th day. P requirement for milk production in the meantime is equal to P present in the milk. P makes a complex with milk protein (casein) present in the milk. Milk contains 4% crude protein and contains 1.04 g P/kg milk. During early lactation, a dairy cow weighing 600 kg needs 1000 g of P (NRC, 2001). It is noted that during the lactation period, the daily dietary requirement of P is 0.32-0.38% P in feed (dry matter (DM) basis). Dry cows require 0.22-0.26% P in feed on DM basis (Satter *et al.* 2005). Researchers have shown that P supplement improves the reproductive performance in dairy cattle. When it comes to beef cattle, the P requirement for maintenance is 16 mg/kg of body weight (Wu *et al.* 2001). For efficient growth, 3.9 g P is needed for each 100g of retained protein. Thus, the beef cow needs 6.2-8.3 g P/day for its maintenance during the gestation period, so that it gets 7.6 g/kg for a calf with a birth weight of 35 kg (Satter *et al.* 2005). During the lactation period, 0.95 g absorbed P is needed to produce 1 kg of milk in beef cattle. Beef cows with a bodyweight between 300-600 kg need 15-16 g P to meet body requirements. According to the NRC (2001) recommendations, beef cattle producing 5-14 kg milk/day consuming a wide range of energy supplements will deliver 0.11-0.24% dietary P (DM basis) to meet daily body requirements (NRC, 2001; Satter *et al.* 2005).

When the dietary P is extremely low, it can inhibit- microbial growth, leading to reduced protein and energy supply to the host animal. However, when it is in excess, it is simply excreted in the manure. Research shows that over 95% of excess P is excreted with faeces. Faecal matter containing 25-50% of microbial origin P from gut microbial fermentation (Wu *et al.* 2001). If the P supplemented through the diet is extremely high, urinary P also reaches a high level. Pi content in the blood serum is maintained at 1.3-2.6 mM under normal conditions and below 1.3 mM when P is deficient. Despite this, plasma Pi is not a significant indicator of P status in ruminants (Lopez *et al.* 2004).

Bones serve as a reserve for P when dietary supplement of P is low. In early lactating beef cows, 30% of bone P is mobilized to meet the P requirement of animals. Deficiency in P in cattle mainly causes due to poor quality forage supplements. A deficiency causes weak and broken bones and poor growth (Wu and Satter, 2000; Wu *et al.* 2000) and severe deficiency can lead to a condition called aphosphorosis. Animals with this disease condition desire to eat wood, bones, rock, and other P containing materials. During the acute stages, animals develop stiffness and lameness in the front quarters. Deficiency is also attributed to a reduction in milk production and calf weaning weight (Karn, 2001).

Role of P in poultry

P is a fundamental structural element of the skeleton next to Ca. Bones store around 85% of the total P content in the body. The rest is in the body fluid as inorganic P; in this 10% of inorganic P is in the blood (Adedokun and Adeola, 2013). P concentration in the blood of healthy birds is 35-45 mg/100 mL of blood (Patterson *et al.* 2005). In poultry, P is essential to attain optimum genetic potential and develop the body frame. In addition, P is compulsory for egg production in the bird. Multiple factors affect birds' Ca and P requirements such as; genotype, age of birds, feed ingredients, Ca and P origins, growth performance, egg production, and egg quality (Pelicia *et al.* 2009; Jiang *et al.* 2013). Unlike ruminants, poultry species cannot optimize phytic P efficiently. Plant-based P sources contained around 70% phytic P; thus, most poultry relies on other P sources to fulfil their requirements. Even in poultry excess supplementation of Ca and P is expelled through faecal matter (Li *et al.* 2017).

The minimum requirement of P in chicks is 0.5%/kg DM and the ratio of Ca to P should be 1.0:1.0 to 2.2:1.10. The requirement of Ca and P in broilers in the early stages of growth are (day 1-14) 6.5 g/kg of DM and 3.5 g/kg of DM in feed (Bailey, 2020). Later on (day 15-21), the bird will need 3.0 g of P/kg of feed and 6.0g of Ca/kg feed. For laying hens, 1.8 g of P/kg feed is needed for egg production from 23 to 47 weeks (Li *et al.* 2017). Deficiency in P affects the bone quality of the broiler, and the main consequence of this is rickets and growth failure. Soft bones, nails, and beaks were observed in birds affected by rickets. Due to the reduced rigidity of bones, crooked backbone and sternum, bending of ribs will occur, finally leading to the bone being bent and broken. Birds are not able to bear their body weight due to weaker bones, walking becomes painful, eventually leading to reduced bird performance (Dinev, 2012). Apart from the economic implications, Ca and P imbalances impact chicken welfare (Driver *et al.* 2005).

Deficiency in cholecalciferol, Ca, and P is associated with leg disorders, which becomes severe as the bird ages (Edwards Jr, 2002; Bar *et al.* 2003). Deficiencies in the growing stage can cause clinical leg bone abnormalities and lameness and these effects are irreversible even if P is supplemented later in the diet. Further abnormalities in the cartilage can cause more serious welfare problems such as osteomyelitis and femoral head necrosis due to bacterial infections (Whitehead, 2002). The short-term lack of P deficiency will not influence the energy metabolism; instead, P will be released by the bones and soft tissue for resorption. Resorption from bone and soft tissue causes urinary loss of P. In severe P deficiency can lead to weakness, loss of appetite and bone development abnormalities (Bar *et al.* 2003).

Phosphorus homeostasis in animal

Ca and P ratio is a crucial factor in P metabolism. Pi enters the bloodstream from dietary Pi, P from bone, and renal reabsorption. P from dietary sources is immediately stored after absorption (Pirgozliev *et al.* 2008). P absorption from the diet is unaffected even when dietary P is excessive. P resorption from skeletal remains is also unaffected by dietary P intake. P Source available in the gut can be either dietary P or endogenous P. Endogenous P are P sources from the body itself (De Matos, 2008). It can reach the gut as digestive secretions such as saliva and secretions from the intestine diffusion from plasma. Endogenous P is mixed well in the gut and absorbed into the intestine similarly to dietary P. Excess P will eventually be excreted from the body through faeces, urine, and sweat. In ruminants, P excretion occurs mainly through faecal matter. In other species, urine is the prime source of excretion (Li *et al.* 2016). Dietary Pi intake takes place in the small intestine, where a higher rate of abortion occurs in the upper and lower jejunum. P absorption can occur by active transportation (60-70%) or facilitated diffusion. Absorption can be either a Na-dependent or Na-independent pathway (Sabbagh *et al.* 2009; Segawa *et al.* 2009). Na dependent pathways are not affected by Ca concentration, and Na- independent pathways occur when P concentration is high in digesta (Sabbagh *et al.* 2009).

A higher P concentration in digesta induces the paracellular transportation of P ion along with intercellular spaces from lumen to blood. The postprandial pathway mainly responds to this type of P transportation. Na-dependent P absorption in the meantime occurs through Na-dependent co-transporters. The translocation occurs across the cell and efflux at the basolateral membrane. NaPi co-transporter type IIb (NaPi-IIb) in the brush border of the ileum is responsible for the Pi Na-dependent pathway. NaPi-IIb co-transporters are significantly less in the duodenum and jejunum (Murer *et al.* 2000; Takeda *et al.* 2004; Adedokun and Adeola, 2013; Li *et al.* 2016). Na absorbs actively from digesta along with a large net water intake. During this process, Pi and Ca are concomitantly absorbed passively down their concentration gradient. The Na gradient in the brush border is maintained by - Na-K ATPase, making P reabsorption indirectly energy-dependent (Proszkowiec and Angel, 2013).

Phosphorus homeostasis is deeply correlated with Ca and vitamin D. Skeletal (bones), renal, and intestine are the three major organs that regulate the homeostasis of Ca and P (Deluca, 2004). The endocrine system mainly controls P homeostasis function. The amount of Ca and P available for metabolism is reflected in the rates of intestinal absorption, bone accretion and resorption, glomerular filtration, renal tubular reabsorption, and endogenous intestinal losses (Li *et al.* 2017).

Endocrine controls of Pi and Ca is primarily regulated by the parathyroid hormone (PTH) and the hormonal form of vitamin D_3 ($1,25(OH)_2D_3$) (Renkema *et al.* 2008). Recent studies show that the fibroblast growth factor 23 (FGF 23) and Klotho are in conjunction with parathyroid and vitamin D_3, and it strictly regulates the Ca and P balance in the body (Shimada *et al.* 2003; Rowe, 2004). FGF 23 is produced in the bone, and it reduces renal reabsorption of P and suppresses the renal formation of calcitriol. Klotho, in the meantime, acts as a membrane-bound co-receptor for FGF23. In addition, estrogen also takes part in Ca and P metabolism in layers. For example, estrogen increases duodenal absorption of Ca and mobilization of labile Ca from medullary bone to form eggshells (Dacke *et al.* 2015).

Key determinants in Pi homeostasis are the glomerular filtration rate and tubular reabsorption rate. Free Pi in serum filtered by the glomerulus and reabsorbed in renal tubule-trans cellular via the Na-dependent pathway depends on the electrochemical gradient present for Na+. Active Pi absorption occurs in the kidney via Na-dependent Pi co-transporters, NaPi-IIa, and NaPi-IIc (Sabbagh *et al.* 2009; Marks *et al.* 2010; Proszkowiec and Angel, 2013). Figure 1 describes the mechanism of maintaining plasma Pi concentration in the animal body when it fluctuated over the level. Disturbances to Ca and Pi homeostasis is linked to pathophysiological disorders, including chronic renal insufficiency, kidney stone formation, and bone abnormalities (Marks *et al.* 2010). Serum Pi concentration thus needs to be strictly maintained within a specific range. Furthermore, the quantities of Ca and P available for metabolism reflect intestinal absorption rates, bone accretion and resorption, glomerular filtration, renal tubular reabsorption, and endogenous intestinal losses (Pines and Reshef, 2015).

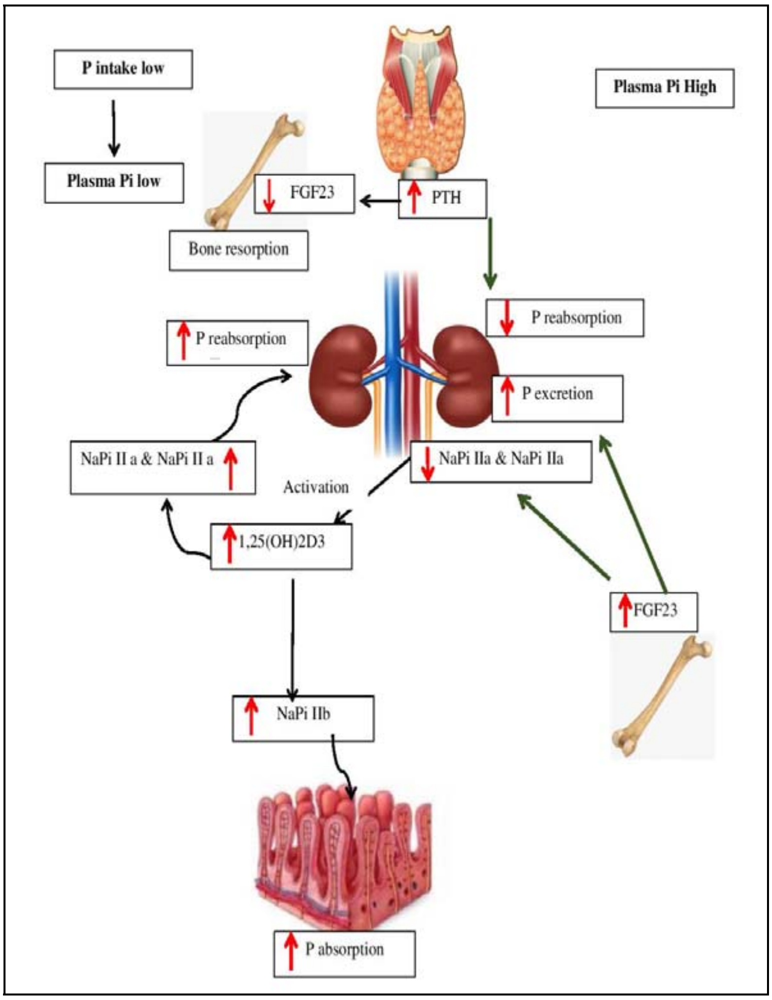

Figure 1 Phosphorus homeostasis in animals

Sources of phosphorus for animals

Phosphate sources for animals can be categorized into plant-based sources, animal-based sources, and inorganic P sources. Natural P sources combine with various elements such as oxygen (O), calcium (Ca), chlorine (Cl), and fluorine (F) (Abouzeid, 2008) in different forms and ranges. The reactivity of P thus can vary according to its chemical composition. The composition and structure of the P source affect the availability of digestible P in different sources (Ajakaiye *et al.* 2003).

Plant material plays a primary role in animal nutrition. Phosphate in plant martial contains around 0.09-1.09% of P, mainly in the form of phytic P (Humer and Zebeli, 2015). An animal's ability to utilize the phytic P differs substantially from species to species. As already discussed, ruminants can digest phytic P due to the nourished microbial content in the rumen. However, non-ruminants have limited ability to digest the phytic P unless it is supplied with extrinsic phytic acid.

Plant material present with intrinsic phytic acid has shown P bioavailability up to some extent. For example, the bioavailability of P in soybean meal, rice bran, wheat bran, and corn are respectively 30-50%, 25%, 29%, and 20% (Selle *et al.* 2003).

Animal sources of P are obtained from fish, meat, and bone meal. Good quality fish and meat meals contain 22 g/kg, 29 g/kg of P, and bone meals contain a high P concentration of around 60 g/kg. The use of animal-based phosphorus supplements has been restricted due to the risk of contamination, especially regarding zoonotic diseases (Li *et al.* 2016).

Inorganic phosphorus is one of the other major categories which offer high digestible P apart from plant origins. Therefore, inorganic P has been widely used for P supplementation in animal husbandry. Poultry accounts for approximately 50% of the animal inorganic feed phosphate consumption worldwide (Neset and Cordell, 2012). Feed grade inorganic phosphate is mainly produced by treating rock phosphate under different conditions to remove contaminants. The main advantage of feed phosphate is obtaining the Ca and P ratio for better bioavailability in animals. Monocalcium phosphate, dicalcium phosphate, calcium sodium phosphate, monosodium phosphate, and diflourinated phosphate are some feed phosphate sources available for feed formulation (Bikker *et al*. 2016). Almost 99% of P in monocalcium phosphate and dicalcium phosphate is bioavailable (Viveros *et al*. 2002).

Recent concerns in phosphorus feeding

Excessive P in feed increases the excretion of faecal and urinary P into the environment, which leads to pollution and eutrophication of water bodies (Smith and Alexander, 2000; Elser *et al*. 2007; Vasconcelos *et al*. 2007). At the same time, inorganic phosphate sources around the world are fast depleting. It assumed that naturally available rock phosphate would be depleted by 2050 (Herrera and Lopez, 2016). Thus, focus has been turned to better utilization of P by optimising available P at the optimum level and recycling and reusing waste containing P for better production. In agriculture, P is wasted as faecal and urinary phosphorus from animal husbandry. P wastage in animal husbandry occurs mainly due to poor nutritional management (Jama-Rodzeńska *et al*. 2021).

Other inorganic forms of dietary Ca and P are more efficiently used by animals when compared to Ca and P, which exist in organic forms. Phosphorus availability in plant sources lacks intrinsic phytase, which reduces the bioavailability of organic phosphorus in plants. Studies show that the bioavailability of P in plant sources varies between 10-60% (Knowlton *et al*. 2004). Apart from phytic phosphorus, a major P source for animal production is inorganic phosphorus and these too differ from each other in their absorbability. Orthophosphates (PO_4^{3-}) are better absorbed than metaphosphates (PO_3^{2-}), and both have better absorbability than pyrophosphates (P_2O^7) (Jama-Rodzeńska *et al*. 2021).

Recent studies have focused on feeding P to animals in highly bioavailable forms from organic and inorganic sources. The bioavailability of phytic P in plant sources like grains and seeds can be increased by adding extrinsic phytic enzymes to cleavage the organic-P complex. Supplementation of microbial phytase in processing techniques is another alternative approach to reduce phytase contents (Knowlton *et al*. 2004; Humer and Zebeli, 2015). Commercially, fungi and bacterial-derived phytase are used in feed formulation for this purpose (Selle and Ravindran, 2007). Present studies also focus on feeding P as nano-particles to increase its dietary absorption and bioavailability (Matuszewski *et al*. 2020). Nano-particles have higher physical activity and chemical neutrality. Therefore, the process increases the surface area of P for enzyme activity and absorption by producing P as nano-particles (Patra and Melody, 2019). Also, recent studies demonstrate the synthesis of nano-particles by beneficial microbes and the production of short-chain fatty acids (Matuszewski *et al*. 2020).

CONCLUSION

Ca and P is the most abundant mineral in the animal body. P possesses a key role in energy metabolism, cell signaling, and forms the backbone nucleic acids. P is a vital mineral and is considered the third most costly component in feed. Feed P can be phytic/organic P or inorganic P. Feeding animals with sufficient amounts of P with Ca and Vit-D increases the absorption of dietary P. Feeding sufficient P to animals improves bone health, product quality and reproductive performance. The requirement of P varies with the species and production parameters of the animal. Identifying an animal's special requirements and feeding them with a source of good quality P improves efficiencies in animal husbandry and reduces its environmental impact.

ACKNOWLEDGEMENT

This research was funded by the World Bank and Ministry of Education, Sri Lanka, under the Accelerating Higher Education Expansion and Development (AHEAD) project (Project no: AHEAD/RA3/DOR/WUSL/LAS/no:57).

REFERENCES

Abouzeid A.Z.M. (2008). Physical and thermal treatment of phosphate ores: an overview. *Int. J. Miner. Process*. **85(4),** 59-84.

Adedokun S. and Adeola O. (2013). Calcium and phosphorus digestibility: Metabolic limits. *J. Appl. Poult. Res*. **22(3),** 600-608.

AFRC. (1993). Energy and Protein Requirements of Ruminants. CAB International, Wallingford, UK.

Ajakaiye A., Atteh J. and Leeson S. (2003). Biological availability of calcium in broiler chicks from different calcium sources found in Nigeria. *Anim. Feed Sci. Technol*. **104(1),** 209-214.

Bailey C.A. (2020). Precision poultry nutrition and feed formulation. Pp. 367-378 in Animal Agriculture: Challenges, Innovations, and Sustainability. F.W. Bazer, G.C. Lamb and G. Wu, Eds. Elsevier, New York.

Bar A., Shinder D., Yosefi S., Vax E. and Plavnik I. (2003). Metabolism and requirements for calcium and phosphorus in the fast-growing chicken as affected by age. *British J. Nutr*. **89(1),** 51-60.

Bhanderi B.M., Goswami A., Garg M.R. and Samanta S. (2016). Study on minerals status of dairy cows and their supplementation through area specific mineral mixture in the state of Jharkhand. *J. Anim. Sci. Technol*. **58,** 42-53.

Bikker P., Spek J.W., Van Emous R.A. and Van Krimpen M.M. (2016) Precaecal phosphorus digestibility of inorganic phosphate sources in male broilers. *British Poult. Sci.* **57(6),** 810-817.

Blaine J., Chonchol M. and Levi M. (2014). Renal control of calcium, phosphate, and magnesium homeostasis. *Clin. J. Am. Soc. Nephrol.* **10(7),** 1257-1272.

Boros L.G., Cascante M. and Paul Lee W.N. (2002). Metabolic profiling of cell growth and death in cancer: Applications in drug discovery. *Drug Discov. Today*. **7(6),** 364-372.

Cavestany D., Blanc J.E., Kulcsar M., Uriarte G., Chilibroste P., Meikle A. and Krall F.E. (2005). Studies of the transition cow under a pasture-based milk production system: Metabolic profiles. *J. Vet. Med. Ser A*. **52(1),** 1-7.

Cromwell G.L. (2005). Phosphorus and swine nutrition. Pp. 607-634 in Phosphorus; Agriculture and the Environment. J.T. Sims and A.N. Sharpley, Eds. American Society of Agronomy, Madison, Wisconsin.

Dacke C.G., Sugiyama T. and Carol V.G. (2015). The role of hormones in the regulation of bone turnover and eggshell calcification. Pp. 549-575 in Sturkie's Avian Physiology. C.G. Scanes, Ed. Elsevier, San Diego.

Deluca H.F. (2004). Overview of general physiologic features and functions of vitamin D. *Am. J. Clin. Nutr.* **80(6),** 1689-1696.

De Matos J. (2008). Calcium metabolism in birds. *Vet. Clin. North Am. Exot. Anim. Pract.* **11(1),** 59-82.

Dinev I. (2012). Clinical and morphological investigations on incidence of forms of rickets and their association with other pathological states in broiler chickens. *Res. Vet. Sci.* **92(2),** 273-277.

Driver J.P., Pesti G.M., Bakalli R.I. and Edwards Jr H.M. (2005). Effects of calcium and nonphytate phosphorus concentrations on phytase efficacy in broiler chicks. *Poult. Sci.* **84(9),** 1406-1417.

Edixhoven J.D., Gupta J. and Savenije H.H.G. (2014). Recent revisions of phosphate rock reserves and resources: A critique. *Earth Syst. Dyn*. **5(2),** 491-507.

Edwards Jr H.M. (2002). Studies on the efficacy of cholecalciferol and derivatives for stimulating phytate utilization in broilers. *Poult. Sci.* **81(7),** 1026-1031.

Elser J.J., Bracken M.E.S., Cleland E.E., Gruner D.S., Harpole W.S., Hillebrand H. and Smith J.E. (2007). Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecol. Lett.* **10(12),** 1135-1142.

Garg M.R., Sherasia P.L., Phondba B.T. and Hossain H.A. (2014). Effect of feeding a balanced ration on milk production, microbial nitrogen supply and methane emissions in field animals. *Anim. Prod. Sci*. **54(10),** 1657-1661.

Herrera E.L. and López A.D. (2016). Phosphorus: The underrated element for feeding the world. *Trends Plant Sci*. **21(6),** 461-463.

Hinkle P.C. (2005). P/O ratios of mitochondrial oxidative phosphorylation. *Biochim. Biophys. Acta*. **1706(1),** 1-11.

Humer W.I.E. and Zebeli Q. (2015). Phytate in feed ingredients and potentials for improving the utilization of phosphorus in ruminant nutrition. *Anim. Feed Sci. Technol*. **209,** 1-15.

Ibtisham F., Nawab A., Guanghui X.M., An Lilong A. and Naseer G. (2018). Effect of nutrition on reproductive efficiency of dairy animals. *Med. Weter*. **74(6),** 356-361.

Jama-Rodzeńska A., Białowiec A., Koziel J.A. and Sowiński J. (2021). Waste to phosphorus: A transdisciplinary solution to P recovery from wastewater based on the TRIZ approach. *J. Environ. Manage*. **287,** 1-16.

Jiang S., Cui L., Shi C., Ken X. and Luo J.H. (2013). Effects of dietary energy and calcium levels on performance, egg shell quality and bone metabolism in hens. *Vet. J.* **198,** 252-258.

Karn J.F. (2001). Phosphorus nutrition of grazing cattle. A review. *Anim. Feed Sci. Technol*. **89(3),** 133-153.

Kiarie E. and Nyachoti C.M. (2010). Bioavailability of calcium and phosphorous in feedstuffs for farm animals. Pp. 76-93 in Phosphorous and Calcium Utilization and Requirements in Farm Animals. D.M.S.S. Vitti and E. Kebreab, Eds. CAB International, Wallingford, United Kingdom.

Knowlton K.F., Radcliffe J.S., Novak C.L. and Emmerson D.A. (2004). Animal management to reduce phosphorus losses to the environment. *J. Anim. Sci*. **82(13),** 173-195.

Kovacs C.S. (2014). The Role of PTHrP in regulating mineral metabolism during pregnancy, lactation, and fetal/neonatal development. *Clin. Rev. Bone. Miner. Metab*. **12,** 142-164.

Lamp A.E., Mereu A., Ruiz-Ascacibar I. and Moritz J.S. (2020). Inorganic feed phosphate type determines mineral digestibility, broiler performance, and bone mineralization. *J. Appl. Poult. Res*. **29(3),** 559-572.

Lanyon L.E. (2005). Phosphorus, animal nutrition and feeding: Overview. Pp. 560-586 in Phosphorus: Agriculture and the Environment. J.T. Sims and A.N. Sharpley, Eds. American Society of Agronomy, Madison, Wisconsin.

Li X., Zhan D. and Bryden W.L. (2017). Calcium and phosphorus metabolism and nutrition of poultry: Are current diets formulated in excess? *Anim. Prod. Sci*. **57,** 2304-2310.

Li X., Zhang D., Yan T.Y. and Bryden W.L. (2016). Phosphorus bioavailability: A key aspect for consblaierving this critical animal feed resource with reference to broiler nutrition. *Agriculter*. **6(2),** 25-35.

Lopez H., Kanitz F.D., Moreira V.R., Wiltbank M.C. and Satter L.D. (2004). Effect of dietary phosphorus on performance of lactating dairy cows: Milk production and cow health. *J. Dairy Sci*. **87(1),** 139-145.

Marks J., Debnam E.S. and Unwin R.J. (2010). Phosphate homeostasis and the renal-gastrointestinal axis. *American J. Physiol. Renal Physiol*. **299(2),** 285-296.

Matuszewski A., Łukasiewicz M. and Niemiec J. (2020). Calcium and phosphorus and their nanoparticle forms in poultry nutrition. *World's Poult. Sci. J*. **76(2),** 1-18.

Moe S.M. (2008). Disorders involving calcium, phosphorus, and magnesium. *Prim. Care Clin Off. Pract*. **35(2),** 215-237.

Murer H., Hernando N., Forster I. and Biber J. (2000). Proximal tubular phosphate reabsorption: Molecular mechanisms. *Physiol. Rev*. **80(4),** 1373-1409.

Neset T.S. and Cordell D. (2012). Global phosphorus scarcity: Identifying synergies for a sustainable future. *J. Sci. Food Agric*. **92(1),** 2-6.

NRC. (2001). Nutrient Requirements of Dairy Cattle. 7th Ed. National Academy Press, Washington, DC., USA.

Patra A. and Melody L. (2019). Progress and prospect of essential mineral nanoparticles in poultry nutrition and feeding: A review. *Biol. Trace Elem. Res.* **197,** 233-253.

Patterson P.H., Moore Jr P.A. and Angel R. (2005). Phosphorus and poultry nutrition. Pp. 635-682 in Phosphorus: Agriculture and the Environment. J.T. Sims and A.N. Sharpley, Eds. American Society of Agronomy, Madison, Wisconsin.

Pelicia K., Garcia E.A., Faitarone A.B.G., Silva A.P., Berto D.A., Molino A.B. and Vercese F. (2009). Calcium and available phosphorus levels for laying hens in second production cycle. *Brazilian J. Poult. Sci.* **11(1),** 39-49.

Pines M. and Reshef R. (2015). Poultry bone development and bone disorders. Pp. 367-377 in Sturkie's Avian Physiology. C.G. Scanes, Ed. Elsevier, San Diego.

Pirgozliev V., Oduguwa O., Acamovic T. and Bedford M.R. (2008). Effects of dietary phytase on performance and nutrient metabolism in chickens. *British Poult. Sci.* **49(2),** 144-154.

Proszkowiec W.M. and Angel R. (2013). Calcium and phosphorus metabolism in broilers: Effect of homeostatic mechanism on calcium and phosphorus digestibility. *J. Appl. Poult. Res.* **22(3),** 609-627.

Puggaard L., Kristensen N.B. and Sehested J. (2011). Effect of decreasing dietary phosphorus supply on net recycling of inorganic phosphate in lactating dairy cows. *J. Dairy Sci.* **94(3),** 1420-1429.

Renkema K.Y., Alexander R.T., Bindels R.J. and Hoenderop J.G. (2008). Calcium and phosphate homeostasis: Concerted interplay of new regulators. *Ann. Med.* **40(2),** 82-91.

Rowe P.S.N. (2004). The wrickkened pathways of FGF23, MEPE and PHEX. *Crit. Rev. Oral Biol. Med.* **15(5),** 264-281.

Sabbagh Y., O'Brien S.P., Song W., Boulanger J.H., Stockmann A., Arbeeny C. and Schiavi S.C. (2009). Intestinal Npt2b plays a major role in phosphate absorption and homeostasis. *J. Am. Soc. Nephrol.* **20(11),** 2348-2358.

Satter D.L., Terry J., Klopfenstein G.E.E. and Powell J.M. (2005). Phosphorus and dairy/beef nutrition. Pp. 587-606 in Phosphorus: Agriculture and the Environment. J.T. Sims and A.N. Sharpley, Eds. American Society of Agronomy, Madison, Wisconsin.

Segawa H., Onitsuka A., Kuwahata M., Hanabusa E., Furutani J., Kaneko I., Tomoe Y., Aranami F., Matsumoto N., Ito M., Matsumoto M., Li M., Amizuka N. and Miyamoto K. (2009). Type IIc sodium-dependent phosphate transporter regulates calcium metabolism. *J. Am. Soc. Nephrol.* **20,** 104-113.

Selle P.H. and Ravindran V. (2007). Microbial phytase in poultry nutrition. *Anim. Feed Sci. Technol.* **135(1),** 1-41.

Selle P.H., Walker A.R. and Bryden W.L. (2003). Total and phytate-phosphorus contents and phytase activity of Australian-sourced feed ingredients for pigs and poultry. *Australian J. Exp. Agric.* **43(5),** 475-479.

Shastak Y., Witzig M., Hartung K. and Rodehutscord M. (2012). Comparison of retention and prececal digestibgargility measurements in evaluating mineral phosphorus sources in broilers1,2. *J. Poult. Sci.* **91(9),** 2201-2209.

Shimada T., Hasegawa H., Yamazaki Y., Muto T., Hino R., Takeuchi Y. and Yamashita T. (2003). FGF-23 is a potent regulator of vitamin D metabolism and phosphate homeostasis. *J. Bone Miner. Res.* **19(3),** 429-435.

Singh J., Hundal J.S., Sharma A., Udeybir S.C., Sethi A.P.S. and Singh P. (2018). Phosphorus nutrition in dairy animals: A review. *Int. J. Curr. Microbiol. Appl. Sci.* **7(04),** 3518-3530.

Smith R.A. and Alexander R.B. (2000). Sources of nutrients in the nation's watersheds. Pp. 13-21 in Proc. Nat. Res. Agric. Engin. Serv. Conf., Camp Hill, Pennsylvania.

Suttle N.F. (2010). Mineral Nutrition of Livestock. CABI, Wallingford, United Kingdom.

Takeda E., Yamamoto H., Nashiki K., Sato T., Arai H. and Taketani Y. (2004). Inorganic phosphate homeostasis and the role of dietary phosphorus. Inorganic phosphate homeostasis and the role of dietary phosphorus. *J. Cell. Mol. Med.* **8(2),** 191-200.

USGS. (2021). Mineral Commodity Summaries, Phosphate Rock, US. Department of the Interior, Washington, DC, USA.

Vasconcelos J.T., Tedeschi L.O., Fox D.G., Galyean M.L. and Greene L.W. (2007). Feeding nitrogen and phosphorus in beef cattle feed lot production to mitigate environmental impacts. *Prof. Anim. Sci.* **23,** 8-17.

Viveros A., Brenes A., Arij I. and Centeno C. (2002). Effects of microbial phytase supplementation on mineral utilization and serum enzyme activities in broiler chicks fed different levels of phosphorus. *Poult. Sci.* **81(8),** 1172-1183.

Westerblad H., Bruton J.D. and Katz A. (2010). Skeletal muscle: Energy metabolism, fiber types, fatigue and adaptability. *Exp. Cell Res.* **316(18),** 3093-3099.

Whitehead C.C. (2002). Nutrition and poultry welfare. *World's Poult. Sci. J.* **58(3),** 349-356.

Wu G., Bryant M.M., Gunawardana P. and Roland D.A. (2007). Effect of nutrient density on performance, egg components, egg solids, egg quality, and profits in eight commercial Leghorn strains during phase one. *Poult. Sci.* **86(4),** 691-697.

Wu Z. and Satter L.D. (2000). Milk production and reproductive performance of dairy cows fed two concentrations of phosphorus for two years. *J. Dairy. Sci.* **83,** 1052-1063.

Wu Z., Satter L.D. and Soja R. (2000). Milk production, reproductive performance, and fecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. *J. Dairy Sci.* **83(5),** 1028-1041.

Wu Z., Satter L.D., Blohoiak A.J., Satuffacher R.H. and Wilson J.H. (2001). Milk production, estimated phosphorus excretion, and bone characteristics of dairy cows fed different amounts of phosphorus for two or three years. *J. Dairy Sci.* **84(7),** 1738-1748.