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— Invited Review —
Mineral composition and phosphorus digestibility in feed phosphates fed to pigs and poultry

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Abstract: Phosphorus (P) is a macro mineral needed for bone mineralization and cell membrane structure and P is also involved in several fundamental pathways of metabolism in the body. Because of the low concentration and digestibility of P in plant ingredients that are the main components of diets for poultry and pigs, feed phosphates are usually included in diets in addition to the P contributed by plant ingredients. The most widely used feed phosphates in poultry and swine diets are dicalcium phosphate (DCP) and monocalcium phosphate (MCP), but tricalcium phosphate (TCP), monosodium phosphate (MSP), and magnesium phosphate (MgP) may be used as well. Because feed phosphates are mostly produced from rock phosphate, feed phosphates have impurities that contain minerals other than P. Concentrations of P in feed phosphates range from 14.8% (MgP) to 25.7% (MSP). The standardized total tract digestibility (STTD) of P in pigs ranges from 71% (TCP) to 95% (MSP). The STTD of Ca and the standardized ileal digestibility (SID) of P and Ca in feed phosphates fed to pigs and poultry have been determined only in a few experiments. Available data indicate that the STTD of Ca and SID of P in MCP are greater than in DCP in both poultry and pigs, but the SID of Ca is similar between DCP and MCP fed to broilers. Information on mineral concentrations and digestibility values in feed phosphates is needed in diet formulation for pigs and poultry, but if diets are formulated to contain equal concentrations of digestible P and Ca, it is unlikely that animal performance will be impacted by the source of feed phosphates used in the diet.

Keywords: Digestibility; Feed Phosphate; Impurity; Mineral; Pig; Poultry

INTRODUCTION

Phosphorus (P) is a macro mineral needed for bone mineralization and cell membrane structure and P is also involved in several fundamental pathways of metabolism in the body. Phosphorus nutrition has been studied more intensely than the nutrition of any other mineral due to its importance in nutrition, high cost, and potential for contributing to pollution of the external environment [1].

Dietary P can be provided by feed ingredients of plant or animal origin. Plant ingredients used in poultry and swine nutrition are mainly grains and co-products from oilseeds, but grain co-products are also used. The concentration of P in cereal grains ranges from 0.18% (polished rice) to 0.38% (triticale), whereas for grain co-products, P concentration ranges from 0.24% (corn gluten meal) to 2.58% (defatted rice bran), and for oilseed meals from 0.52% (palm kernel expellers) to 1.22% (dehulled sunflower meal) [2]. However, up to 92% of total P in plant feed ingredients is phytate-bound [2-4], which results in low utilization of P from plants by poultry and pigs [5,6]. Fish meal, meat and bone meal, blood meal, and co-products of milk are the main animal-origin ingredients that are used in poultry and swine diets [7-9]. Because P in animal-origin ingredients is not bound to phytate, it is highly digestible to pigs whereas P from plants generally has low digestibility [1,5]. However, animal-origin ingredients are mostly used for weanling pigs, whereas diets for growing-finishing pigs, sows, and poultry primarily contain plant ingredients.

Because of the low concentration and digestibility of P in plant ingredients, feed phosphates are usually included in diets for pigs and poultry in addition to the P contributed by plant- and animal-origin ingredients [10]. Mineral concentrations, digestibility values, and physicochemical characteristics of feed phosphates are therefore of importance to the poultry and swine feed industry. However, summarized data on characteristics and P digestibility in feed phosphates fed to poultry and pigs are limited. Therefore, the objective of the current work was to review current knowledge about feed phosphates used in the poultry and swine feed industries and to summarize data on P digestibility in feed phosphates fed to pigs and poultry.

FEED PHOSPHATES USED IN POULTRY AND SWINE NUTRITION

The most widely used feed phosphates are dicalcium phosphate (DCP) and monocalcium phosphate (MCP) [11], but tricalcium phosphate (TCP), monosodium phosphate (MSP), and magnesium phosphate (MgP) may be used as well [12-14].

Concentrations of P in feed phosphates range from 14.8% (MgP) to 25.7% (MSP; Table 1). The concentration of dry matter (DM) in DCP, MCP, MgP, and MSP is greater than 90% and the concentration of ash is greater than 78%. The difference between DM and ash is a result of the loss of crystalline water, carbon dioxide, and volatile minerals during the ashing procedure [12,15]. Crystalline water originates from some of the phosphate salts in feed phosphates, whereas carbon dioxide is lost from carbonates that usually also are present in feed phosphates.

Dicalcium phosphate and monocalcium phosphate

Feed phosphates are products of the wet processing crushing of phosphate rock from volcanic or sedimentary origin. Phosphorus is extracted from the rock and released in the form of phosphoric acid (H_3PO_4) after reaction of the rock with sulfuric acid although hydrochloric acid may also be used (Figure 1) [16,17]. A second reaction in which phosphoric acid is reacted with calcium carbonate ($CaCO_3$) results in the production of DCP ($CaHPO_4$) and MCP [$Ca(H_2PO_4)_2$; Figure 2] [18]:

Table 1. Concentrations of macro- and micro-minerals in feed phosphates[1)]

Item	DCP	MCP	TCP	MSP	MgP
Dry matter (%)	94.9±0.60	93.0±0.78	-	99.2±0.41	96.6
Ash (%)	83.3±1.41	79.6±0.62	-	88.3±3.03	86.4
Macro minerals (%)					
Ca	21.3±2.40	16.7±0.44	34.2	0.7±0.45	1.0
P	19.2±0.28	21.9±0.86	17.7	25.7±1.95	14.8
Mg	0.7±0.51	0.7±0.42	0.4	<0.1	24.7
Na	<0.1	<0.1	6.0	20.5±0.00	0.7
K	0.1±0.02	0.1±0.02	-	<0.1	0.1
S	0.4±0.21	0.2±0.07	-	<0.1	1.7
Micro minerals					
Co (mg/kg)	3.1±2.21	3.0±2.21	-	<2.3	4.0
Cu (mg/kg)	7.7±6.77	8.7±7.20	-	<0.6	2.0
F (%)	0.1±0.02	0.2±0.04	-	<0.1	0.1
Fe (%)	0.7±0.50	0.6±0.44	-	<0.3	0.3
Mn (%)	0.04±0.02	0.04±0.02	-	<0.1	<0.1
Zn (mg/kg)	89.0±66.03	123.4±72.28	-	28.0±27.00	50.0
Other minerals (mg/kg)					
Al	553.4±452.59	437.1±492.14	-	1,124±456.00	161.0
As	5.7±1.48	6.0±3.26	-	1.0±0.60	1.0
Cd	3.1±2.41	3.5±2.52	-	0.3±0.08	0.2
Hg	<0.1	<0.1	-	<0.1	<0.1
Pb	0.8±0.30	1.2±1.14	-	0.1±0.04	0.2
Si	3,159±1,753	3,496±2,047	-	387.5±26.50	17,300
Free H_2O (%)	<0.2	<0.1	-	<0.1	<0.1

DCP, dicalcium phosphate; MCP, monocalcium phosphate; TCP, tricalcium phosphate; MSP, monosodium phosphate; MgP, magnesium phosphate.
1) Information on analyzed concentrations of minerals in DCP, MCP, MSP, and MgP were from 4, 7, 2, and 1 sources, respectively [49]; values for concentrations of minerals in TCP were obtained from NRC [3].

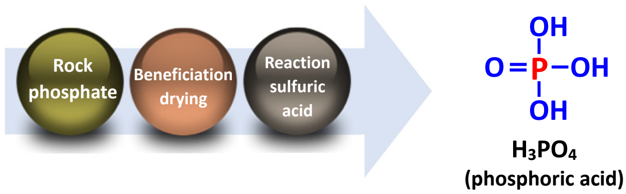

Figure 1. Production of phosphoric acid.

DCP: $H_3PO_4 + CaCO_3 \rightarrow H_2O + CO_2 + CaHPO_4$,
MCP: $2(H_3PO_4) + CaCO_3 \rightarrow H_2O + CO_2 + Ca(H_2PO_4)_2$.

The reaction of phosphoric acid with calcium carbonate will naturally reach a chemical equilibrium that results in a mixture of DCP and MCP [19,20]. In commercial sources of calcium phosphates that are produced in the U.S., Ca concentrations are more variable among different sources compared with concentrations of P because the reaction between phosphoric acid and calcium carbonate is stopped according to the amount of total P desired in the final product. Producers of DCP and MCP have to guarantee a minimum concentration of P in the final products, which is controlled by the amount of phosphoric acid that is added to calcium carbonate. The reaction is usually stopped at 18.5% P to produce DCP, but the reaction continues until the product contains 21.0% P if MCP is produced. Therefore, final products have a relatively constant concentration of P, but variations in Ca concentrations are often observed. However, because the production of DCP and MCP is a continuous process, feed phosphates that are sold as DCP or MCP usually contain both DCP and MCP and the only difference is that there is less DCP in a product designated as MCP than if the product is designated as DCP [19,21]. Dicalcium phosphate can be present in both anhydrate ($CaHPO_4$) and hydrate forms ($CaHPO_4{\cdot}H_2O$ or $CaHPO_4{\cdot}2H_2O$), but MCP exists mainly in a monohydrate form [$Ca(H_2PO_4)_2{\cdot}H_2O$]. Neutralization of phosphoric acids with calcium carbonate results in a slurry that contains DCP in the hydrated form, but heating at 65°C to 70°C is needed

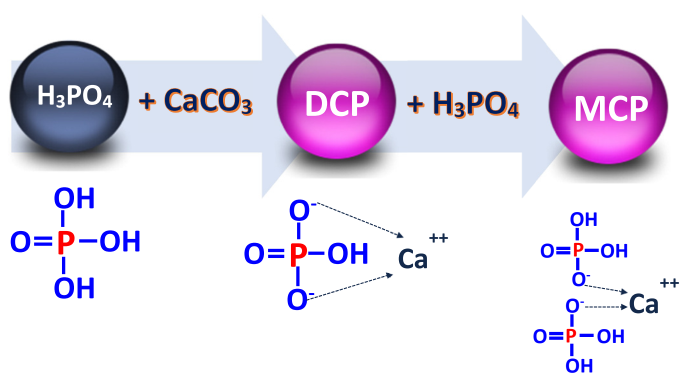

Figure 2. Production of DCP and MCP. DCP, dicalcium phosphate; MCP, monocalcium phosphate.

Table 2. Mineral composition of commercial dicalcium phosphate (DCP) and monocalcium phosphate (MCP)[1)]

Component (%)	Chemical formula	DCP	MCP
Calcium carbonate	$CaCO_3$	6.74	6.00
DCP and MCP			
MCP	$Ca(H2PO_4)_2{\cdot}H_2O$	14.19	60.98
DCP	$CaHPO_4$	26.42	12.54
Dihydrated DCP	$CaHPO_4{\cdot}2(H_2O)$	34.65	-
Others			
Phosphoric acid	H_3PO_4	0.80	1.00
Silica	SiO_2	0.15	0.13
Calcium fluoride	CaF_2	0.32	0.44
Sodium phosphate	$NaH_2PO_4{\cdot}2(H_2O)$	0.54	0.61
Free water	H_2O	0.80	1.00
Aluminum phosphate	$AlPO_4$	2.21	2.48
Ferrous phosphate	$FePO_4{\cdot}2(H_2O)$	2.65	2.98
Calcium sulfate	$CaSO_4{\cdot}H_2O$	3.51	3.95
Magnesium phosphate	$Mg(H_2PO_4)_2{\cdot}4(H_2O)$	7.02	7.89
Total		100.00	100.00

[1)] Adapted from [19].

to dry the slurry, which results in some of the hydrated DCP becoming anhydrated DCP ($CaHPO_4$). In commercial DCP, approximately 35% is in the dihydrated form (Table 2).

In pure sources of DCP (molecular weight = 136.1 g/mol) and MCP (molecular weight = 234.05 g/mol), concentrations of P are 22.8% and 26.5%, respectively, and concentrations of Ca are 29.5% and 17.1%, respectively. However, feed grade sources of these ingredients have lower concentrations of P and Ca. The reason is that minerals other than Ca and P are present in feed grade phosphates along with unreacted calcium carbonate. Therefore, although the process of producing feed grade MCP and DCP is designed to eliminate impurities that may be harmful to animals, other minerals are usually present in feed phosphates, which is often due to impurities in the calcium carbonate that is used in the production process. Some of the minerals considered impurities in feed phosphate such as Mg, S, Fe, Al, and Na can form phosphate salts including magnesium phosphate [$Mg(H_2PO_4)_2 \cdot 4H_2O$], calcium sulfate ($CaSO_4 \cdot H_2O$), ferrous phosphate ($FePO_4 \cdot 2H_2O$), aluminum phosphate ($AlPO_4$), and others [19]. Therefore, the calcium phosphates typically used in the feed industry contain several minerals other than P and Ca.

Tricalcium phosphate

Tricalcium phosphate [$Ca_3(PO_4)_2$] is produced by reacting phosphoric acid with calcium carbonate to form calcium dihydrogen phosphite [$Ca(H_2PO_3)_2$] followed by calcination above 900°C:

$Ca(H_2PO_3)_2 + 2Ca(OH)_2$ + natural gas → (calcination) → $Ca_3(PO_4)_2$.

When the phosphoric acid is neutralized, calcium phosphate hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, is also formed [22,23]. The pure forms of TCP and hydroxyapatite are not used in animal feeds, but defluorinated rock phosphate, which is commercially available, is known as feed grade TCP because it mainly contains TCP [12]. By applying the high temperature during the calcination process, sulfur or fluorine that are considered harmful to animals are mostly removed [24], but some Na from the original rock remains in the final product (<5.5%) [12]. Feed-grade TCP is used in poultry diets, but it is not frequently included in diets for pigs in North America. However, some countries in Asia use TCP as source of Ca and P in diets for pigs.

Monosodium phosphate

Monosodium dihydrogen phosphate is produced from the reaction of phosphoric acid and sodium hydroxide or carbonate [20]. The reaction between phosphoric acid and sodium hydroxide (NaOH) or sodium carbonate (Na_2CO_3) is the initial reaction to produce MSP and depending on the manufacturer, different reagents are used:

Using NaOH: $H_3PO_4 + 3NaOH \rightarrow Na_3PO_4 + 3H_2O$
Using Na_2CO_3: $2H_3PO_4 + 3Na_2CO_3 \rightarrow 2Na_3PO_4 + 3H_2CO_3$.

The end product of the initial reactions is trisodium phosphate (Na_3PO_4), but treatment with water in scrubbers results in the production of monosodium dihydrogen phosphate (NaH_2PO_4; Figure 3) [25].

The concentration of P in feed grade MSP is greater than 24% [3]. Requirements for Na can be met by the inclusion of salt in the diets, which also will result in Cl meeting the requirement [3], and MSP is, therefore, rarely used as a source of Na in practical diets for pigs. However, MSP is sometimes used in research diets for pigs and because of the high digestibility of P in MSP, it is often used as the standard to estimate the relative bioavailability of P in different feed ingredients [11,26,27].

Magnesium phosphate

Magnesium phosphate ($MgHPO_4$) may be produced by a double decomposition reaction between disodium phosphate and magnesium salts or by neutralizing solutions containing magnesium salts and phosphoric acids with caustic soda (NaOH; Figure 4) [22]. Most MgP salts are in hydrated forms ($MgHPO_4 \cdot H_2O$). Commercial MgP often has a greater concentration of S than other feed phosphates, but even if MgP is used to provide the majority of P in diets, the concentration of S will be less than the concentration that is expected

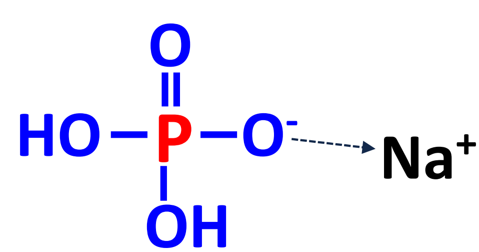

Figure 3. Chemical structures of MSP (NaH_2PO_4). monosodium phosphate; MSP, monosodium phosphate.

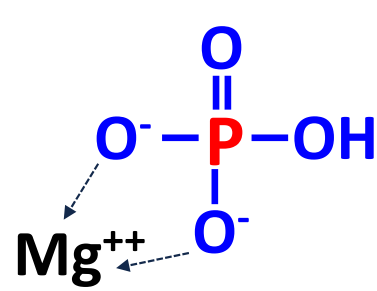

Figure 4. Chemical structures of MgP (MgHPO4). MgP, magnesium phosphate.

to negatively affect growth of pigs due to the low inclusion of feed phosphates in the final diets and the relatively low absorption of S in the pig [3,28]. Magnesium is usually not added to practical diets for pigs, but MgP is sometimes used in mineral premixes if feed ingredients with low availability of Mg are used [3]. Magnesium phosphate is also used in animal nutrition, especially in ruminants, because deficiency of Mg is more common in forage-based diets for ruminant animals. The trihydrate form [$MgHPO_4 \cdot 3(H_2O)$] is the only stable form at 25°C.

DIGESTIBILITY OF P IN FEED PHOSPHATES

Determination of digestibility of P in pigs and poultry

Historically, values for the relative bioavailability of P in feed ingredients were generated using MSP or MCP as the standard [29] and these values were used to formulate diets for pigs [30]. However, values for the relative bioavailability of P are not always additive in mixed diets, and values vary depending on the digestibility of P in the standard [11]. It was, therefore, recognized that formulating diets based on values for digestible P is more accurate than using values for the relative bioavailability of P [3].

Because P is mostly absorbed before the end of the small intestine, there is no difference between values for ileal digestibility and total tract digestibility of P [31-33], although some hindgut disappearance of P in pigs has been reported ([34-36]). Because it is easier and less expensive to measure total tract digestibility of P than ileal digestibility of P, total tract digestibility of P is usually measured. By correcting the apparent total tract digestibility of P for the basal endogenous losses of P, values for the standardized total tract digestibility (STTD) of P are calculated. Values for the STTD of P are not influenced by the concentration of P in the diet and those values are, therefore, not underestimated if the concentration of P in the diet is low [37]. Values for the STTD of P are also additive in a mixed diet [38,39], which is a prerequisite for accurate diet formulation. It is, therefore, recommended that diets for pigs are formulated based on the STTD of P in individual ingredients [3].

Values for total tract digestibility of P in poultry are difficult to obtain because the excreta of chickens contains both fecal and urine excretions. Therefore, ileal digestibility of P in feed ingredients fed to poultry may be determined to exclude urinary excretion in the excreta [40]. Because values for standardized ileal digestibility (SID) of P are additive [41] and are not affected by dietary P [40], the SID of P in various feed ingredients fed to broilers has been determined. However, information on the SID of P in feed phosphates fed to poultry is limited.

STTD and SID of P in feed phosphates fed to pigs and broiler chickens

Values for the STTD of P vary among different feed phosphates fed to pigs (Figure 5). Among calcium phosphates, the STTD of P in MCP (93%) is the greatest, followed by DCP (89%) and TCP (71%). The SID of P in feed phosphates has been determined only in one experiment. Among DCP, MCP, and TCP, the SID of P in MCP (89.3%) is the greatest, followed by DCP (79.5%) and TCP (56.7%) if the feed phosphates are fed to broilers chickens [42].

It appears that P in a calcium phosphate is better digested and absorbed if the calcium phosphate contains less Ca. This may be a result of the interaction between dietary Ca and P, which forms an indigestible Ca-P complex that precipitates

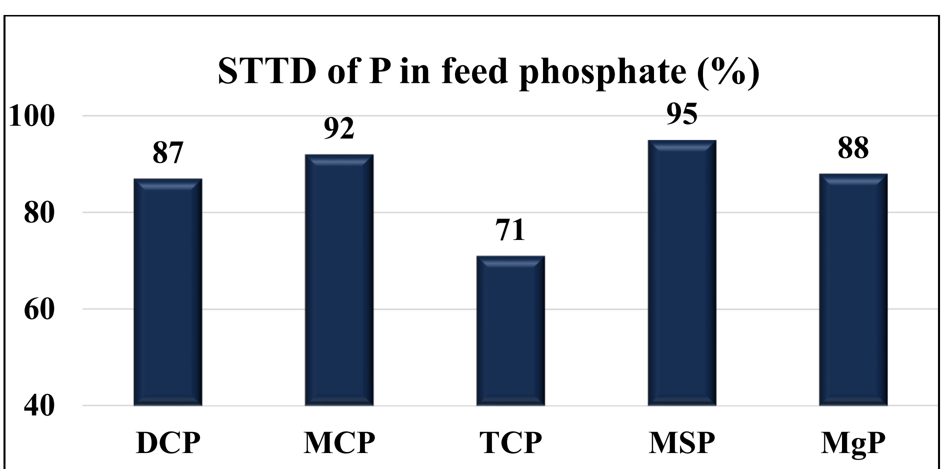

Figure 5. Standardized total tract digestibility (STTD) of P (%) in feed phosphate fed to pigs. DCP, dicalcium phosphate; MCP, monocalcium phosphate; TCP, tricalcium phosphate; MSP, monosodium phosphate; MgP, magnesium phosphate. Data from Petersen and Stein [21]; NRC [3]; Baker et al [54]; Kwon and Kim [48]; and Lopez [49].

in the intestinal tract of pigs [43,44], but more research is needed to confirm this hypothesis. Most commercial DCP is in the anhydrous form, but (di-)hydration of P molecules may increase the digestibility of P in DCP fed to pigs, because hydrated DCP is more soluble in the intestinal tracts, and thus has a greater digestibility, than the anhydrous form [5, 10,45-47].

The STTD of P in MgP (88%) fed to pigs is less than in MCP and MSP, but greater compared with TCP. The STTD of P in MSP is greater than in calcium phosphates or MgP [3,21,48,49]. This observation is likely the reason MSP was often used as the standard in experiments conducted to determine the relative bioavailability of P in feed ingredients.

STTD and SID of Ca in DCP and MCP fed to pigs and broiler chickens

The STTD of Ca in feed ingredients has been determined because digestible Ca is more additive in mixed diets if values are corrected with endogenous losses [50]. Use of exogenous phytase may increase the STTD of Ca in calcium carbonate and some other feed ingredients, but that is not the case for the STTD of Ca in MCP and DCP [51,52]. However, the STTD of Ca in feed phosphates has been determined only in a few experiments. The STTD of Ca in MCP (86%) is likely greater than in DCP (77%) [51]. However, because of the greater concentration of Ca in DCP than in MCP, the concentration of standardized total tract digestible Ca in DCP is close to that in MCP. Variations in the STTD of Ca among different sources of DCP and MCP appear to be low [52].

The SID by broiler chickens of Ca in DCP and MCP was summarized by Walk et al [53], although not many experiments have determined the SID of Ca in feed phosphates fed to poultry. The SID of Ca in both DCP and MCP fed to broilers is 36%, which is much lower compared with pigs.

CONCLUSION

The current contribution discussed how feed phosphates are produced, how much P and other minerals are included in each feed phosphate, and how much P is utilized if they are fed to pigs and poultry. Production of feed phosphates has been designed to meet a minimum concentration of P using phosphate rock, which results in variations in concentrations of other minerals. Feed phosphate sources contain 15% to 26% P and values for the STTD of P vary with different feed phosphates. Information on both mineral concentrations and digestibility values in feed phosphates is needed in diet formulation for pigs and poultry because each source contains different concentrations of digestible P. However, if diets are formulated to contain equal concentrations of digestible P and Ca, it is unlikely that animal performance will be impacted by the source of feed phosphates used in the diet.

CONFLICT OF INTEREST

We certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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REFERENCES

1. Kiarie E, Nyachoti CM. Bioavailability of calcium and phosphorus in feedstuffs for farm animals. In: Vitti DM, Kebreab E, editors. Phosphorus and calcium utilization and requirements in farm animals. London, UK: CAB International 2010. p. 76-93.
2. Stein HH, Lagos LV, Casas GA. Nutritional value of feed ingredients of plant origin fed to pigs. Anim Feed Sci Technol 2016;218:33-69. https://doi.org/10.1016/j.anifeedsci.2016.05.003
3. NRC. Nutrient requirements of swine. 11th rev. ed. Washington, DC, USA: National Academies Press; 2012.
4. Lee SA, Stein HH. Analyzed values for P and phytate in feed ingredients. Stein Nutrition Newsletter. June, [Internet]. Urbana, IL, USA c2021 [cited 2022, Oct]. Available from: https://nutrition.ansci.illinois.edu/node/1753
5. Zhai H, Adeola O, Liu J. Phosphorus nutrition of growing pigs. Anim Nutr 2022;9:127-37. https://doi.org/10.1016/j.aninu.2022.01.010
6. Papp M, Sommerfeld V, Schollenberger M, Avenhaus U, Rodehutscord M. Phytate degradation and phosphorus utilisation by broiler chickens fed diets containing wheat with increased phytase activity. Br Poult Sci 2022;63:375-85. https://doi.org/10.1080/00071668.2021.1966756
7. Kim H, Lee SH, Kim BG. Effects of dietary spray-dried plasma protein on nutrient digestibility and growth performance in nursery pigs. J Anim Sci 2021;100:skab351. https://doi.org/10.1093/jas/skab351
8. Kong C, Kim KH, Ji SY, Kim BG. Energy concentration and phosphorus digestibility in meat meal, fish meal, and soybean meal fed to pigs. Anim Biosci 2021;34:1822-8. https://doi.org/10.5713/ab.21.0102
9. Zanu HK, Keerqin C, Kheravii SK, et al. Influence of meat and bone meal, phytase, and antibiotics on broiler chickens challenged with subclinical necrotic enteritis: 1. growth performance, intestinal pH, apparent ileal digestibility, cecal microbiota, and tibial mineralization. Poult Sci 2020;99:1540-50. https://doi.org/10.1016/j.psj.2019.11.021
10. Jongbloed AW, Everts H, Kemme PA. Phosphorus availability and requirements in pigs. In: Haresign W, Cole DJA, editors. Recent advances in animal nutrition. Oxford, UK: Butterworth-

Heinemann; 1991. p. 65-80.
11. Petersen GI, Pedersen C, Lindemann MD, Stein HH. Relative bioavailability of phosphorus in inorganic phosphorus sources fed to growing pigs. J Anim Sci 2011;89:460-6. https://doi.org/10.2527/jas.2009-2161
12. Lima FR, Fernandes JIM, Oliveira E, Fronzaglia GC, Kahn H. Laboratory evaluations of feed-grade and agricultural-grade phosphates. Poult Sci 1999;78:1717-28. https://doi.org/10.1093/ps/78.12.1717
13. O'Connor AM, Beede DK, Wilcox CJ. Lactational responses to dietary magnesium, potassium, and sodium during winter in Florida. J Dairy Sci 1988;71:971-81. https://doi.org/10.3168/jds.S0022-0302(88)79643-5
14. Cromwell GL, Stahly TS, Coffey RD, Monegue HJ, Randolph JH. Efficacy of phytase in improving the bioavailability of phosphorus in soybean meal and corn-soybean meal diets for pigs. J Anim Sci 1993;71:1831-40. https://doi.org/10.2527/1993.7171831x
15. Lima FR, Mendonça CX, Alvarez JC, et al. Chemical and physical evaluations of commercial dicalcium phosphates as sources of phosphorus in animal nutrition. Poult Sci 1995;74:1659-70. https://doi.org/10.3382/ps.0741659
16. Leikam DF, Achorn FP. Phosphate fertilizers: Production, characteristics, and technologies. In: Sims JT, Sharpley AN, editors. Phosphorus: agriculture and the environment. Madison, WI, USA: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2005. p. 23-50.
17. Stewart WM, Hammond LL, Kauwenbergh SJV. Phosphorus as a natural resource. In: Sims JT, Sharpley AN, editors. Phosphorus: Agriculture and the environment. Madison, WI, USA: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America; 2005. p. 3-22.
18. Speight JG. Industrial inorganic chemistry. In: Speight JG, editor. Environmental inorganic chemistry for engineers. Oxford, UK: Butterworth-Heinemann; 2017. p. 111-69.
19. Baker DH. Phosphorus sources for poultry. Multi-State Poult. Newsl; 1989;1:5-6.
20. Gard DR. Phosphoric acids and phosphates. Kirk-Othmer encyclopedia of chemical technology. Hoboken, NJ, USA: John Wiley & Sons; 2005. https://doi.org/10.1002/0471238961.1608151907011804.a01.pub2
21. Petersen GI, Stein HH. Novel procedure for estimating endogenous losses and measurement of apparent and true digestibility of phosphorus by growing pigs. J Anim Sci 2006;84:2126-32. https://doi.org/10.2527/jas.2005-479
22. Schrödter K, Bettermann G, Staffel T, et al. Phosphoric acid and phosphates. In: Ley C, editor. Ullmann's encyclopedia of industrial chemistry. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2008.
23. Rey C, Combes C, Drouet C, Grossin D. 1.111 - Bioactive ceramics: physical chemistry. In: Ducheyne P, editor. Comprehensive biomaterials. Oxford, UK: Elsevier; 2011. p. 187-221.
24. Butt CA. Manufacture of defluorinated tricalcium phosphate. Lake Forest, IL, USA: International Minerals and Chemical Corp; 1948.
25. U.S. Environmental Protection Agency. Acid digestion of sediments, sludges, and soils [cited 2022, Aug]. Washington, DC, USA: US EPA; 1996. Available from: https://www.epa.gov/sites/production/files/2015-12/documents/3050b.pdf
26. Spencer JD, Allee GL, Sauber TE. Phosphorus bioavailability and digestibility of normal and genetically modified low-phytate corn for pigs. J Anim Sci 2000;78:675-81. https://doi.org/10.2527/2000.783675x
27. Weremko D, Fandrejewski H, Zebrowska T, et al. Bioavailability of phosphorus in feeds of plant origin for pigs-Review-. Asian-Australas J Anim Sci 1997;10:551-66. https://doi.org/10.5713/ajas.1997.551
28. McGlone JJ, Pond WG. Pig production: Biological principles and applications. Independence, KY, USA: Delmar Learning, Thomson Learning; 2003.
29. Cromwell GL, Hays VW, Scherer CW, Overfield JR. Effects of dietary calcium and phosphorus on performance and carcass, metacarpal and turbinate characteristics of swine. J Anim Sci 1972;34:746-51. https://doi.org/10.2527/jas1972.345746x
30. NRC. Nutrient requirements of swine. 10th rev. ed. Washington, DC, USA: National Academies Press; 1998.
31. Ajakaiye A, Fan MZ, Archbold T, et al. Determination of true digestive utilization of phosphorus and the endogenous phosphorus outputs associated with soybean meal for growing pigs. J Anim Sci 2003;81:2766-75. https://doi.org/10.2527/2003.81112766x
32. Bohlke RA, Thaler RC, Stein HH. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J Anim Sci 2005;83:2396-403. https://doi.org/10.2527/2005.83102396x
33. Zhang F, Ragland D, Adeola O. Comparison of apparent ileal and total tract digestibility of calcium in calcium sources for pigs. Can J Anim Sci 2016;96:563-9. https://doi.org/10.1139/cjas-2016-0043
34. Dilger RN, Adeola O. Estimation of true phosphorus digestibility and endogenous phosphorus loss in growing pigs fed conventional and low-phytate soybean meals. J Anim Sci 2006;84:627-34. https://doi.org/10.2527/2006.843627x
35. Fan MZ, Archbold T, Sauer WC, et al. Novel methodology allows simultaneous measurement of true phosphorus digestibility and the gastrointestinal endogenous phosphorus outputs in studies with pigs. J Nutr 2001;131:2388-96. https://doi.org/10.1093/jn/131.9.2388
36. Shen Y, Fan MZ, Ajakaiye A, Archbold T. Use of the regression analysis technique to determine the true phosphorus digestibility and the endogenous phosphorus output associated

with corn in growing pigs. J Nutr 2002;132:1199-206. https://doi.org/10.1093/jn/132.6.1199

37. Kim BG, Lee JW, Stein HH. Energy concentration and phosphorus digestibility in whey powder, whey permeate, and low-ash whey permeate fed to weanling pigs. J Anim Sci 2012;90:289-95. https://doi.org/10.2527/jas.2011-4145
38. Kwon WB, Park SK, Kim BG. Determination of additivity of apparent and standardized total tract digestibility of phosphorus in mixed diet fed to growing pigs. J Anim Sci 2015;93 (E-Suppl. s3):75 (Abstr.).
39. She Y, Wang QY, Stein HH, Liu L, Li D, Zhang S. Additivity of values for phosphorus digestibility in corn, soybean meal, and canola meal in diets fed to growing pigs. Asian-Australas J Anim Sci 2018;31:1301-7. https://doi.org/10.5713/ajas.17.0547
40. Rodehutscord M, Dieckmann A, Witzig M, Shastak Y. A note on sampling digesta from the ileum of broilers in phosphorus digestibility studies. Poult Sci 2012;91:965-71. https://doi.org/10.3382/ps.2011-01943
41. Babatunde OO, Osho SO, Park CS, Adeola O. Additivity of apparent and standardized ileal digestibility of phosphorus in mixed diets containing corn and soybean meal fed to broiler chickens. Poult Sci 2020;99:6907-13. https://doi.org/10.1016/j.psj.2020.09.022
42. An SH, Sung JY, Kong C. Ileal digestibility and total tract retention of phosphorus in inorganic phosphates fed to broiler chickens using the direct method. Animals 2020;10:2167. https://doi.org/10.3390/ani10112167
43. Lee SA, Lagos LV, Bedford MR, Stein HH. Increasing calcium from deficient to adequate concentration in diets for gestating sows decreases digestibility of phosphorus and reduces serum concentration of a bone resorption biomarker. J Anim Sci 2020;98:skaa076. https://doi.org/10.1093/jas/skaa076
44. Stein HH, Adeola O, Cromwell GL, Kim SW, Mahan DC, Miller PS. Concentration of dietary calcium supplied by calcium carbonate does not affect the apparent total tract digestibility of calcium, but decreases digestibility of phosphorus by growing pigs. J Anim Sci 2011;89:2139-44. https://doi.org/10.2527/jas.2010-3522
45. Grimbergen AHM, Cornelissen JP, Stappers HP. The relative availability of phosphorus in inorganic feed phosphates for young turkeys and pigs. Anim Feed Sci Technol 1985;13:117-30. https://doi.org/10.1016/0377-8401(85)90047-1
46. Eeckhout W, de Paepe M. The digestibility of three calcium phosphates for pigs as measured by difference and by slope-ratio assay. J Anim Physiol Anim Nutr 1997;77:53-60. https://doi.org/10.1111/j.1439-0396.1997.tb00737.x
47. Shastak Y, Witzig M, Hartung K, Rodehutscord M. Comparison of retention and prececal digestibility measurements in evaluating mineral phosphorus sources in broilers. Poult Sci 2012;91:2201-9. https://doi.org/10.3382/ps.2011-02063
48. Kwon WB, Kim BG. Standardized total tract digestibility of phosphorus in various inorganic phosphates fed to growing pigs. Anim Sci J 2017;88:918-24. https://doi.org/10.1111/asj.12785
49. Lopez DAL. Composition and digestibility of different sources of feed phosphates by growing pigs [M. S. Thesis]. Urbana-Champaign, IL, USA: University of Illinois Urbana-Champaign; 2020.
50. Zhang F, Adeola O. True is more additive than apparent total tract digestibility of calcium in limestone and dicalcium phosphate for twenty-kilogram pigs fed semipurified diets. J Anim Sci 2017;95:5466-73. https://doi.org/10.2527/jas2017.1849
51. González-Vega JC, Walk CL, Stein HH. Effects of microbial phytase on apparent and standardized total tract digestibility of calcium in calcium supplements fed to growing pigs. J Anim Sci 2015;93:2255-64. https://doi.org/10.2527/jas.2014-8215
52. Lee SA, Lagos LV, Walk CL, Stein HH. Standardized total tract digestibility of calcium varies among sources of calcium carbonate, but not among sources of dicalcium phosphate, but microbial phytase increases calcium digestibility in calcium carbonate. J Anim Sci 2019;97:3440-50. https://doi.org/10.1093/jas/skz176
53. Walk CL, Romero LF, Cowieson AJ. Towards a digestible calcium system for broiler chicken nutrition: A review and recommendations for the future. Anim Feed Sci Technol 2021;276:114930. https://doi.org/10.1016/j.anifeedsci.2021.114930
54. Baker SR, Kim BG, Stein HH. Comparison of values for standardized total tract digestibility and relative bioavailability of phosphorus in dicalcium phosphate and distillers dried grains with solubles fed to growing pigs. J Anim Sci 2013;91:203-10. https://doi.org/10.2527/jas.2010-3776