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Non ruminant nutrition

Digestibility of calcium in calcium-containing ingredients and requirements for digestible calcium by growing pigs

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Abstract

The concentration of Ca in plant feed ingredients is low compared with the requirement for pigs and most Ca in diets for pigs is provided by limestone and Ca phosphate. To determine digestibility values for Ca that are additive in mixed diets, the standardized total tract digestibility (**STTD**) of Ca needs to be calculated, and the STTD of Ca by growing pigs in most Ca-containing ingredients has been reported. Although Ca is an inexpensive nutrient compared with P and amino acids, excess Ca needs to be avoided because excess dietary Ca results in reduced P digestibility, reduced feed intake, and reduced growth performance of pigs. Recent data indicate that most diets produced for pigs in the United States and Europe contain ~0.20 percentage units more Ca than formulated, which likely is because of the use of limestone as a carrier in feed additives or as a flow agent in other ingredients. An excess of this magnitude without a corresponding excess of P will result in a reduction in daily gain of growing pigs by 50 to 100 g. Greater emphasis, therefore, needs to be placed on determining the concentration of Ca in diets for pigs. Microbial phytase increases the digestibility of both Ca and P and it is, therefore, important that the release of both Ca and P by phytase is considered in diet formulation. However, due to the relationship between Ca and P in postabsorptive metabolism, diets need to be formulated based on a ratio between digestible Ca and digestible P. To maximize average daily gain, this ratio needs to be less than 1.40:1.0 in diets for weanling pigs, and the ratio needs to be reduced as the body weight of pigs increases. In contrast, to maximize bone ash, the digestible Ca to digestible P ratio needs to increase from 1.67:1.0 in 11 to 25 kg pigs to 2.33:1.0 in finishing pigs. Gestating sows have reduced STTD and retention of Ca and P compared with growing pigs and formulation of diets for sows based on digestibility values obtained in growing pigs will result in inaccuracies in the provision of Ca and P. There is, however, a lack of data for the digestibility of Ca and P by gestating and lactating sows, and responses to microbial phytase by sows are not fully understood. There is, therefore, a need for research to generate more data in this area. In the present review, a summary of data for the digestibility of Ca in feed ingredients for pigs and estimates for the requirement for digestible Ca by growing and finishing pigs are provided.

Lay summary

Concentration of Ca in most plant feed ingredients is low compared with the requirement for pigs and dietary Ca is, therefore, mostly provided by limestone and calcium phosphates. Although Ca is an inexpensive nutrient compared with P and amino acids, excess dietary Ca may result in reduced P digestibility, feed intake, and growth performance of pigs. Excretion of P from pigs is increased if dietary Ca is provided above the requirement, which may increase environmental pollution. Therefore, determination of the digestibility of Ca in dietary sources of Ca and formulation of diets based on the ratio between digestible Ca and digestible P are needed to reduce Ca and P excretions. This review provides a summary of values for the digestibility of Ca in feed ingredients and also provides estimates for the requirement for digestible Ca by weanling and growing-finishing pigs. Summarized data from experiments that determined the requirement for digestible Ca demonstrated that there are linear correlations between body weight of growing-finishing pigs and digestible Ca to digestible P ratios needed to maximize growth or bone ash.

Key words: calcium, calcium digestibility, calcium requirements, phosphorus, phytase, pigs

Abbreviations: ATTD, apparent total tract digestibility; DCP, dicalcium phosphate; DMI, dry matter intake; MCP, monocalcium phosphate; STTD, standardized total tract digestibility; TTTD, true total tract digestibility

Introduction

The concentration of Ca in most feed ingredients from plants is low compared with the requirement for pigs and because plant ingredients make up the majority of the diets for pigs, most Ca is provided by Ca carbonate, limestone, monocalcium phosphate (**MCP**), or dicalcium phosphate (**DCP**). Excess dietary Ca reduces the digestibility of P (Stein et al., 2011; Lee et al., 2020), which may reduce feed intake and growth performance (González-Vega et al., 2016b; Merriman et al., 2017; Lagos et al., 2019a, 2019b). Because excess Ca reduces P digestibility, excretion of P increases if dietary Ca is provided above the requirement, which may increase environmental pollution (Knowlton et al., 2004).

Diets for pigs are usually formulated based on values for total Ca in feed ingredients, and Ca requirements have previously been based on maintaining a Ca to P ratio of ~1.25 to 1 (NRC, 1998). However, over the last few decades, requirements for P have been based on digestible P rather than total

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P and currently, the requirement for total Ca is calculated as 2.15 times the requirement for standardized total tract digestible P (NRC, 2012). It has, however, been acknowledged that diet formulation based on digestible Ca may be more accurate than formulation based on total Ca (NRC, 2012). Therefore, values for the digestibility of Ca in feed ingredients used in diets for pigs have been determined in recent years, and it is now possible to formulate diets based on standardized total tract digestibility (**STTD**) of Ca rather than total Ca (Lagos et al., 2021b).

Most P in plant feed ingredients is stored as part of phytate, but dietary phytate is negatively correlated with the digestibility of P and Ca by growing pigs (Almaguer et al., 2014; Misiura et al., 2018), and most commercial diets for pigs are, therefore, fortified with microbial phytase to increase the digestibility of P. However, microbial phytase increases the digestibility of Ca in Ca carbonate and many other feed ingredients, although there is no effect of phytase on digestibility of Ca in MCP or DCP (González-Vega et al., 2015a; Lee et al., 2019b). Therefore, to predict the concentration of digestible Ca in a diet, the Ca that is released by phytase in each ingredient needs to be considered in diet formulation.

In addition to phytate and other dietary factors, digestibility of Ca and P is also affected by the physiological status of pigs. Most values for digestibility of Ca and P have been determined in ingredients fed to growing pigs and these values are subsequently applied to all categories of pigs, including gestating sows. However, digestibility of Ca and P by sows is different from the digestibility in growing pigs (Lee et al., 2021), and there are also differences among sows depending on the stage of the reproductive cycle (Lee et al., 2019a). As a consequence, it is not accurate to formulate diets for sows using digestibility values for Ca and P obtained in growing pigs and digestibility values for Ca and P obtained in weanling, growing, or finishing pigs should, therefore, not be applied to sows.

The objective of the present contribution is to provide a summary of values for the digestibility of Ca in feed ingredients, without or with microbial phytase, and to provide estimates for requirements for digestible Ca by weanling and growing-finishing pigs. Values for the suggested digestible Ca to digestible P ratios needed to maximize growth performance or bone ash in weanling or growing-finishing pigs are also provided. It is, however, not the objective of this work to discuss all aspects of Ca nutrition in pigs, and it is acknowledged that many aspects of Ca nutrition that are not related to the digestibility of Ca are equally important and deserve consideration when formulating diets for pigs. It is also acknowledged that great contributions to our understanding of Ca metabolism and utilization have been made by many research teams around the world, which are not included in the present review because the current contribution specifically is focused on discussing Ca digestibility, requirements for digestible Ca, and factors that influence Ca digestibility.

Calcium in Commercial Diets

Calcium is often over-supplied in diets for pigs because limestone (i.e., calcium carbonate) is less expensive than other feed ingredients and therefore is generously supplied in diets (Walk, 2016; Lagos et al., 2023). Limestone is also sometimes used as a carrier in vitamin and mineral premixes and in premixes containing feed additives and limestone may be used as a flow agent in some feed ingredients including soybean meal, distillers dried grains with solubles, and bakery meal resulting in variable concentrations of Ca in these ingredients. As an example, the concentration of Ca in 20 sources of soybean meal collected from crushing plants in the United States ranged from 0.25% to 0.75% (Figure 1; Sotak-Peper et al., 2016), and in 46 sources of bakery meal produced in the United States, Ca varied between 0.05% and 1.34% (Liu et al., 2018). The digestibility of Ca originating from limestone may be different from the digestibility of Ca originating from the ingredient it is added to, but it is not possible to make a distinction between the two sources of Ca because the amount of added limestone usually is not known to the user of the ingredient. It is, therefore, not possible to take this into account in diet formulation. Nevertheless, the combined effects of adding excess limestone to diets, Ca in premixes that is not accounted for in diet formulation, and the use of limestone as a flow agent in some ingredients often lead to greater Ca concentrations in diets than formulated (Walk, 2016; Wu et al., 2018). As an example, the average concentration of Ca in swine and poultry diets is approximately 0.20 percentage units greater than formulated values (Walk, 2016; Lagos et al., 2023). An oversupply with Ca of this magnitude will reduce average daily gain in growing-finishing pigs by 50 to 100 g per day unless dietary P is also supplied in excess of the requirement (González-Vega et al., 2016a; Merriman et al., 2017). Therefore, Ca in premixes and feed additives need to be accounted for in diet formulation and Ca in main feed ingredients needs to be analyzed before diet formulation to avoid oversupplying dietary Ca. Analysis of Ca in mixed diets is also recommended to confirm correct inclusion of Ca in diets without over-supplementation.

The STTD of P by growing pigs and gestating sows decreases as dietary Ca increases from below to at or above the requirement (Figure 2; Stein et al., 2011; Lee et al., 2020). This is likely due to increased chelation with Ca^{2+} ions by phytate in plant feed ingredients as dietary Ca increases, which results in undigestible phytate–Ca–P complexes (Stein et al., 2011). It is also possible that dietary Ca binds directly to P ions in the intestinal tract of pigs to create undigestible Ca–P complexes, which results in precipitation and, therefore, reduction

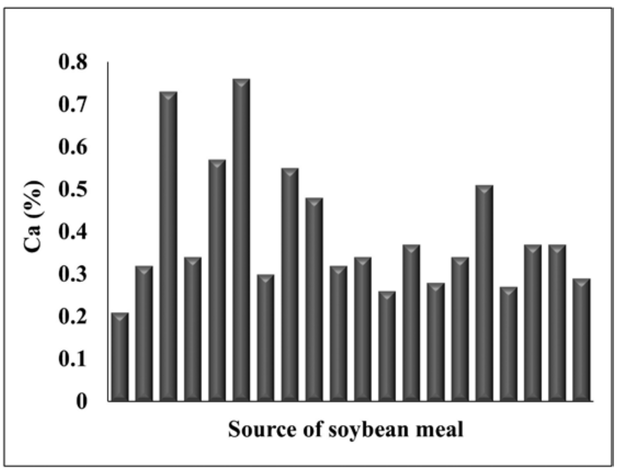

Figure 1. Concentration of Ca in 20 sources of soybean meal collected from crushing plants in the United States. Data modified from Sotak-Peper et al. (2016).

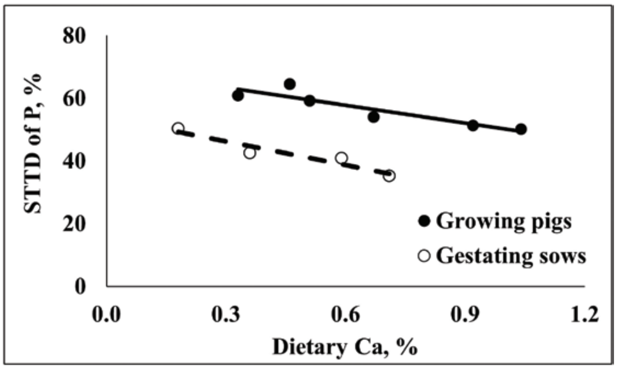

Figure 2. Negative linear correlations between total dietary Ca and digestibility of P in growing pigs (solid dots and straight line) and gestating sows (empty dots and dashed line). Data modified from Stein et al. (2011) and Lee et al. (2020).

in digestibility (Walk et al., 2012; Lautrou et al., 2021). As a consequence, the reduced average daily gain that is a result of oversupplying Ca in diets is likely a result of reduced P absorption, which may create a P deficiency because feed intake is reduced if pigs are fed diets deficient in P (Harper et al., 1994; Gonzalo et al., 2018).

Phytate, Phytase, and Ca

Phytic acid or phytate consists of an inositol ring and six phosphates that are attached to the inositol ring by ester bonds (Figure 3). In grains and oilseeds, phytate serves as a concentrated and stable storage form of P, which can be mobilized and utilized by the developing plant embryo during germination and early growth. As a consequence, most plant feed ingredients that are commonly used in swine diets have high concentrations of phytate-bound P relative to total P (Table 1; Rojas and Stein, 2012; Lee and Stein, 2021). Phosphorus bound to phytate may be released by the enzyme phytase, but pigs secrete very limited quantities of phytase and are, therefore, not able to release most of the phytate-bound P in feed ingredients, which is the reason pigs have low digestibility of phytate-bound P. As a consequence, exogenous phytase is commonly used in commercial diets to increase digestibility of P from phytate, which reduces the need for supplemental phosphate in diets and also results in reduced excretion of P in the manure (Adeola and Cowieson, 2011; Lautrou et al., 2021). Phytate may bind positively charged cations including Ca^{2+} because of the negatively charged reactive sites on the phytate molecule, which results in chelated mineral-phytate compounds that may precipitate in the intestinal tract (Nelson and Kirby, 1987; González-Vega et al., 2015a). Because Ca is invariably associated with P because of its role in the formation of body bone tissues and because Ca is the quantitatively dominating mineral in diets for pigs, the interaction between phytate and Ca has been investigated. Theoretically, phytates generate a maximum of 12 negative charges, which theoretically can bind up to six Ca^{2+}. Supplementation of phytase to diets often results in a greater increase in Ca digestibility than in P digestibility (Almeida et al., 2013), even though the substrate for phytase is phytate. This is because of the different number of Ca^{2+} released by each dephosphorylation compared with the number of phosphates released. If all six reactive sites are

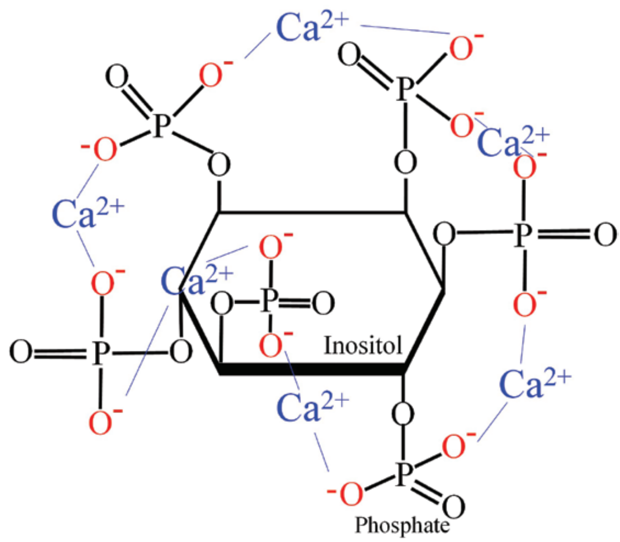

Figure 3. Structural formula of phytate and example of forming undigestible complex between phytate and Ca^{2+}.

chelated with Ca^{2+}, which is not always the case, two Ca^{2+} are released when the first ester bond between P and phytate is hydrolyzed. However, for the next four ester bonds being hydrolyzed, one Ca^{2+} is released for each dephosphorylation, and if the last P is released, no Ca^{2+} will be released. As a consequence, the ratio between Ca^{2+} and P released changes depending on the number of ester bonds being hydrolyzed by phytase, which is largely depending on the amount of phytase being added to the diets. The amounts of phytase added to commercial diets for pigs usually is insufficient to hydrolyze all ester bonds between P and phytate and the number of Ca^{2+} released by phytase is, therefore, usually greater than the number of phosphates released. However, although Ca^{2+} is the dominant cation in diets, other cations including Zn^{2+} may be chelating phytate and in that case, not all reactive sites are occupied by Ca^{2+}. Indeed, inclusion of high levels of ZnO in diets for pigs reduces the efficiency of phytase (Blavi et al., 2017). Calcium from plant ingredients, as well as Ca from Ca carbonate, tend to bind to phytate in the stomach of pigs to form the Ca-phytate complexes (Selle et al., 2009; González-Vega et al., 2015b), but because Ca in MCP or DCP is bound to phosphate, Ca from DCP or MCP is less likely to bind to phytate. As a consequence, inclusion of phytase in a diet will usually increase the digestibility of Ca from limestone and Ca carbonate, but not from MCP and DCP (González-Vega et al., 2015b; Walk, 2016; Lee et al., 2019b). Likewise, phytase may increase the digestibility of Ca in some animal proteins including fish meal (González-Vega et al., 2015b), and this is likely due to Ca from these proteins being solubilized in the stomach and subsequently bound to phytate in the plant ingredients, which makes them unavailable for absorption unless phytase is used. Therefore, the concentration of dietary phytate is negatively correlated with the digestibility of Ca and P by growing pigs (Almaguer et al., 2014; Misiura et al., 2018), whereas microbial phytase increases the digestibility of Ca and P (Almeida et al., 2013; Rodríguez et al., 2013; González-Vega et al., 2015b). Phytate can also bind to other nutrients including protein and amino acids in the intestinal tract, which may result in precipitation of non-digestible nutrient-phytate complexes and reduced

Table 1. Concentrations of phytate and associated Ca and P in feed ingredients used in experiments conducted at the University of Illinois, 2007 to 2022 (as-is basis)

Feed ingredient	Phytate, %			Ca, %			P, %		
	$\bar{x}$	*n*	SD	$\bar{x}$	*n*	SD	$\bar{x}$	*n*	SD
Bakery meal	0.65	55	0.27	0.26	55	0.23	0.33	55	0.09
Barley	0.71	2	0.10	0.05	2	0.02	0.32	2	0.06
Canola expellers	3.15	10	0.26	0.72	10	0.07	1.09	10	0.07
Canola meal	3.09	79	0.47	0.75	78	0.16	1.12	79	0.14
Copra expellers	0.90	3	0.10	0.07	3	0.03	0.51	3	0.02
Copra meal	0.79	4	0.01	0.04	4	-	0.52	4	-
Corn	0.67	49	0.10	0.02	43	0.02	0.26	49	0.07
Corn germ	2.97	3	1.43	0.04	3	0.03	1.13	3	0.48
Corn germ meal	1.90	5	0.22	0.12	5	0.09	0.79	5	0.10
Corn gluten feed	0.71	3	—	0.12	3	-	0.87	3	-
Corn gluten meal	1.66	6	0.04	0.03	6	0.03	0.56	6	0.02
Corn, high protein	0.82	1	—	0.26	1	-	0.01	1	-
Corn DDGS, high oil, > 9% oil	0.53	6	0.30	0.11	6	0.09	0.81	6	0.04
Corn DDGS, low oil, 5% to 9% oil	1.14	6	0.50	0.09	6	0.10	0.82	6	0.05
Corn DDGS, defatted, <5% oil	0.91	2	1.08	0.07	2	0.04	0.94	2	0.10
Corn, hominy feed	2.07	1	—	0.01	1	-	0.70	1	-
Corn DDG, high protein	0.41	2	—	0.02	2	0.01	0.38	2	0.02
Cottonseed meal	2.65	2	0.78	0.24	2	0.02	1.14	2	0.23
Field peas	0.80	6	0.04	0.09	6	0.001	0.47	6	0.03
Lemna protein concentrate	0.15	2	—	0.45	2	-	0.51	2	-
Oats	0.67	1	—	0.16	1	-	0.32	1	-
Palm kernel expellers	1.25	4	0.10	0.28	4	0.07	0.53	4	0.01
Palm kernel meal	1.18	3	0.10	0.22	3	0.03	0.53	3	0.01
Potato protein concentrate (isolate)	0.29	11	0.07	0.03	11	0.001	0.11	11	0.03
Rice bran, full fat	5.95	5	0.14	0.05	5	0.01	1.99	5	0.19
Rice bran, defatted	7.52	3	1.57	0.11	3	0.11	2.35	3	0.40
Rice mill feed	2.01	1	—	0.01	1	-	0.63	1	-
Rice, broken	0.22	2	—	0.09	2	0.11	0.11	2	-
Rice, brown	0.79	2	—	0.01	2	-	0.27	2	-
Rye, hybrid	0.74	5	0.09	0.06	5	0.06	0.28	5	0.03
Sorghum	0.80	6	0.10	0.03	6	0.04	0.30	6	0.02
Soy protein concentrate	1.41	1	—	0.50	1	-	0.62	1	-
Soybeans, full-fat	1.36	12	0.17	0.26	11	0.03	0.58	12	0.07
Soybeans, full-fat, fermented	1.26	1	—	0.31	1	-	0.53	1	-
Soybean expellers	1.60	10	0.61	0.27	6	-	0.78	10	0.01
Soybean hulls	0.19	1	—	0.57	1	-	0.16	1	-
Soybean meal, high CP (CP ≥ 47%)	1.56	68	0.18	0.39	63	0.17	0.66	68	0.08
Soybean meal, low CP (CP < 47%)	1.66	30	0.18	0.37	30	0.29	0.63	30	0.05
Soybean meal, fermented	0.96	9	0.67	0.28	7	0.10	0.61	9	0.16
Sugar beet pulp	0.14	2	—	0.87	2	-	0.70	2	-
Sunflower expellers	1.99	1	—	0.22	1	-	0.48	1	-
Sunflower meal, partially dehulled	2.88	9	0.51	0.34	8	0.05	0.93	9	0.26
Sunflower, full-fat	1.80	1	—	0.10	1	-	0.70	1	-
Triticale	0.74	1	—	0.16	1	-	0.38	1	-
Wheat	1.02	3	0.21	0.03	3	0.03	0.40	3	0.04
Wheat, hard red	0.89	2	0.15	0.05	2	0.02	0.36	2	-
Wheat, soft red	1.15	1	—	0.03	1	—	0.36	1	—
Wheat germ	2.06	1	—	0.09	1	—	0.88	1	—
Wheat middlings	3.00	11	0.55	0.12	11	0.02	1.08	11	0.16
Yeast brewers	1.03	1	—	0.18	1	—	1.40	1	—
Yeast, torula	0.25	1	—	0.13	1	—	1.78	1	—

digestibility of amino acids. However, although phytase has increased amino acid digestibility in some experiments (Espinosa et al., 2022; Lagos et al., 2022), phytase does not always increase amino acid digestibility in diets fed to pigs and inconsistent results among experiments have been reported (Adeola and Cowieson, 2011; Velayudhan et al., 2015; Cowieson et al., 2017; Mesina et al., 2018; She et al., 2018a). It is possible that it takes a greater amount of phytase to increase digestibility of other nutrients compared with what is needed to maximize Ca and P digestibility because the increases in digestibility of other nutrients are smaller than the increases in digestibility of Ca and P (Lagos et al., 2022).

The quantity of phytase that is added to commercial swine diets is usually between 250 and 1,000 phytase units/kg of diet although up to 2,500 units may sometimes be used (Walk, 2016). The efficiency of dietary exogenous phytase depends on the concentration of phytate in the diets (Selle et al., 2009; Adeola and Cowieson, 2011), and the efficacy of phytase is reduced if diets have a wide Ca to P ratio (Lei et al., 1994; Qian et al., 1996; Brady et al., 2002).

Sources of Ca in Diets for Pigs

Most dietary Ca is supplied by mineral supplements, but ingredients of animal-origin or plant-origin may also provide dietary Ca. Mineral supplements mostly include calcium carbonate, limestone, MCP, and DCP, and concentrations of Ca in Ca supplements range from 15% to 40% (NRC, 2012). Limestone, DCP, and MCP are the three most commonly used Ca sources in pig diets. Calcium carbonate is the major component of ground limestone and chemically pure Ca carbonate contains 40.0% Ca (Table 2). Theoretically, based on the total molecular mass, DCP ($CaHPO_4$) and MCP [$Ca(H_2PO_4)_2$] should contain 29.46% and 17.12% Ca, respectively, and the concentration of P should be 22.77% and 26.47% P, respectively (Lee et al., 2023). However, most commercial feed grade DCP and MCP contain less Ca and P compared with expected values, which is the result of impurities in DCP and MCP (Table 3; Baker, 1989). The reason for the impurities is that Ca phosphates are produced by reacting phosphoric acid (H_3PO_4) with limestone and impurities from either H_3PO_4 or limestone result in impurities in DCP and MCP. Therefore, most DCP and MCP in North America that are used in animal diets contain ~24.8% and 16.9% Ca and 18.5% and 21.0% P, respectively (Baker, 1989; Lee et al., 2023).

Table 2. Total molecular weight of Ca carbonate, dicalcium phosphate (DCP), monocalcium phosphate (MCP), and percentage composition of chemically pure Ca supplements

	Total molecular mass, g/mol	Percentage, %
Calcium carbonate [$CaCO_3$]		
Ca × 1	40.08	40.04
C × 1	12.01	12.00
O × 3	48.00	47.96
Total	100.09	100.00
DCP [$CaHPO_4$]		
Ca × 1	40.08	29.46
H × 1	1.01	0.74
P × 1	30.97	22.77
O × 4	64.00	47.04
Total	136.06	100.00
MCP [$Ca(H_2PO_4)_2$]		
Ca × 1	40.08	17.12
H × 4	4.03	1.72
P × 2	61.95	26.47
O × 8	128.00	54.69
Total	234.05	100.00

Cereal grains and co-products of cereal grains and oilseed meals can also provide dietary Ca. However, most cereal grains are very low in Ca (i.e., < 0.05%), and cereal grain co-products usually contain less than 0.15% Ca. Oilseed meals and other plant co-products contain between 0.20% and 0.87% Ca (Table 1). Animal-origin feed ingredients including milk products, fish meal, and animal byproducts contain more Ca compared with plant feed ingredients, and the Ca in these feed ingredients ranges from 0.20% to 8.28% Ca (NRC, 2012; Sulabo and Stein, 2013).

Calcium Digestibility

The digestibility of a nutrient represents the amount of that nutrient that disappears from the intestinal tract and it is generally assumed that this amount is also available for metabolism after absorption (Stein, 2017). Measurement of total tract digestibility is used to determine the digestibility of Ca and P because there is limited net absorption or secretion of Ca and P into the large intestine (Fan and Sauer, 2002a; Bohlke et al., 2005; González-Vega et al., 2014; Zhang et al., 2016).

Values for apparent total tract digestibility (**ATTD**) of a nutrient are often influenced by dietary nutrient levels because not only dietary nutrients that have not been digested and absorbed, but also nutrients of endogenous origin are excreted in the fecal output. Therefore, ATTD values may be underestimated if pigs are fed a diet that is low in the nutrient the ATTD is determined for (Fan et al., 2001; Zhai and Adeola, 2012). Endogenous losses from pigs consist of basal endogenous losses and diet specific endogenous losses. Basal endogenous losses are considered an inevitable loss from the body that is related to dry matter intake (**DMI**), whereas diet specific endogenous losses are losses that are influenced by dietary components (Stein et al., 2007). Values for ATTD can be corrected for basal endogenous losses or total endogenous losses to calculate STTD or true total tract digestibility (**TTTD**), respectively. Because STTD or TTTD values are not affected by the level of nutrients in the diet, values for STTD and TTTD of Ca and P are additive in mixed diets (Table 4; Kwon, 2016; Zhang and Adeola, 2017b; She et al., 2018b). Therefore, diet formulation is more accurate if STTD or TTTD values are used rather than values for ATTD, but due to the difficulties in determining total endogenous losses, values for STTD of Ca and P is usually used in practical diets because that only requires determination of basal endogenous losses.

Values for the basal endogenous loss of P that are estimated using a P-free diet are relatively constant for growing pigs regardless of body weight and the average of a number of experiments indicated that a value of 190 mg/kg DMI is representative of the basal endogenous loss of P by growing pigs (NRC, 2012; Lee and Stein, 2023). However, the basal

Table 3. Mineral composition of commercial sources of limestone, dicalcium phosphate (DCP) and monocalcium phosphate (MCP)[1,2]

Component	Chemical formula	Limestone	DCP (18.5% P)	MCP (21.0% P)
Ca carbonate, %	$CaCO_3$	91.8	6.74	6.00
DCP and MCP				
Monocalcium phosphate, %	$Ca(H_2PO_4)_2 \cdot H_2O$	—	14.19	60.98
Dicalcium phosphate, %	$CaHPO_4$	—	26.42	12.54
Hydrated dicalcium phosphate, %	$CaHPO_4 \cdot H_2O$	—	34.65	—
Others				
Silica, %	SiO_2	3.5	0.15	0.13
Calcium fluoride, %	CaF_2	—	0.32	0.44
Sodium phosphate, %	$NaH_2PO_4 \cdot 2H_2O$	—	0.54	0.61
Phosphoric acid, %	H_3PO_4	—	0.80	1.00
Water, %	H_2O	—	0.80	1.00
Aluminum phosphate, %	$AlPO_4$	—	2.21	2.48
Aluminum oxide, %	Al_2O_3	2.5	—	—
Ferrous phosphate, %	$FePO_4 \cdot 2H_2O$	—	2.65	2.98
Calcium sulfate, %	$CaSO_4 \cdot H_2O$	—	3.51	3.95
Magnesium oxide, %	$CaMg(CO_3)_2$	2.2	—	—
Magnesium phosphate, dibasic, %	$Mg(H_2PO_4)_2 \cdot 4H_2O$	—	7.02	7.89
Total		100.00	100.00	100.00
Nutrient composition				
Calcium, %[3]	Ca	38.5	24.8	16.9
Phosphorus, %[3]	P	—	18.8	21.5
Zinc[4], mg/kg	Zn	—	89.0	123.4

[1]Values for limestone are estimated from Spiropoulos (1985) and unpublished data from the University of Illinois (2017).
[2]Values for DCP and MCP are adapted from Baker (1989).
[3]Values are from NRC (2012).
[4]Values are from Lee et al. (2023).

Table 4. Additivity of values for apparent total tract digestibility (ATTD), standardized total tract digestibility (STTD), and true total tract digestibility (TTTD) of Ca and P in mixed diets fed to growing pigs

Feed ingredients in diets	ATTD				STTD				TTTD			
	Measured[1]	Predicted[1]	Diff.	SE	Measured	Predicted	Diff.	SE	Measured	Predicted	Diff.	SE
Calcium												
Limestone, dicalcium phosphate[2]	69.3	68.1	1.3†	—	—	—	—	—	73.7	72.7	1.1	—
Phosphorus												
Barley, canola meal[3]	22.8	23.8	−1.0	—	—	—	—	—	—	—	—	—
Wheat, pea[3]	45.1	38.1	7.0*	—	—	—	—	—	—	—	—	—
Soybean meal, oat, rough rice, broken rice, corn[4]	15.5	27.3	−11.8*	5.3	—	—	—	—	40.4	42.0	−1.6	3.9
Soybean meal, buckwheat, pea,faba bean, sorghum[4]	21.2	29.9	−8.7*	4.9	—	—	—	—	42.3	41.0	1.3	3.0
Wheat, soybean meal[5]	45.1	41.3	3.8†	1.6	49.7	47.8	1.9	1.6	—	—	—	—
Corn, soybean meal[6]	40.9	42.8	1.9	3.0	44.7	49.0	−4.3	3.0	—	—	—	—
Corn, soybean meal, canola meal[6]	41.0	37.0	−4.0*	1.1	44.1	42.9	1.3	1.1	—	—	—	—

[1]Predicted values were calculated using digestibility values for Ca or P in the individual feed ingredients and the inclusion rate in mixed diets.
[2]Zhang and Adeola (2017b).
[3]Fan and Sauer (2002a).
[4]Fang et al. (2007).
[5]Kwon (2016).
[6]She et al. (2018b).
*Measured and predicted values differ, $P < 0.05$.
†Measured and predicted values tend to be different, $0.05 < P < 0.10$.

endogenous loss of Ca that is estimated from pigs fed a Ca-free, corn-based diet appears to be more variable and values ranging from 329 to 659 mg/kg DMI have been reported (Table 5). The total endogenous losses of Ca and P have also been determined using a regression procedure that regresses digested Ca or P against the intake of that nutrient (Fan and Sauer, 2002b; Zhang and Adeola, 2017a), but values from the regression procedure tend to be more variable than values obtained after feeding a P-free or a Ca-free diet.

The ATTD and STTD of Ca in most commonly used feed ingredients have been determined in recent years (Table 6). The digestibility of Ca is greatest in some of the animal feed ingredients, followed by mineral supplements and plant feed ingredients. Calcium digestibility in Ca carbonate and some

Table 5. Basal endogenous loss of Ca from growing pigs fed a corn-based Ca-free diet[1]

Item	*N*	Average	SD	CV, %	Min.	Max.
Initial body weight, kg	8	16	3.2	19.4	10.2	19.8
Basal endogenous losses of Ca, mg/kg DMI[2]	8	471	101.8	21.6	329	659

[1]Data are from 8 experiments (González-Vega et al., 2015a; Merriman and Stein, 2016; Merriman et al., 2016b; Blavi et al., 2017; Lee et al., 2019b, 2021; Sung et al., 2020; Nelson et al., 2022).
[2]DMI, dry matter intake.

Table 6. Apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of Ca in feed ingredients without and with microbial phytase fed to growing pigs

Item, %	ATTD of Ca		STTD of Ca	
Supplementation of phytase[1]	–	+	–	+
Mineral supplements				
Monocalcium phosphate[2]	83	83	86	86
Dicalcium phosphate[2, 3, 4]	72	76	79	79
Ca carbonate[2,3,4,5,6,7,8,9,10,11]	68	76	72	80
Lithothamnium calcareum[2]	63	66	65	69
Plant feed ingredients				
Barley[11]	70	97	86	100
Canola meal[8, 9, 12]	41	—	45	70
Corn[11,13]	51	83	66	97
Rye, hybrid[11]	73	88	88	100
Sorghum[11]	55	76	69	90
Soybean meal[8, 9, 13]	53	—	78	—
Sugar beet co-product[2]	66	63	68	65
Sunflower meal[8,9]	28	48	31	53
Wheat[11]	76	93	90	100
Animal feed ingredients				
Meat and bone meal[14]	75	—	77	82
Meat meal[14]	75	—	77	86
Fish meal[15]	62	71	65	73
Poultry meal[14]	85	74	82	76
Poultry by product meal[14]	81	84	88	87
Skim milk powder[8]	95	—	97	—
Whey powder[8]	97	—	99	—
Whey permeate[8]	90	—	94	—

[1]Phytase level varied from 300 to 1,500 phytase units/kg diet.
[2]González-Vega et al. (2015b).
[3]Modified from Zhang and Adeola (2017b).
[4]Lee et al. (2019b).
[5]Blavi et al. (2017).
[6]Merriman and Stein (2016).
[7]Merriman et al. (2016a).
[8]Unpublished data from the University of Illinois.
[9]Zhang et al. (2016).
[10]Kwon and Kim (2017).
[11]Modified from McGhee and Stein (2019).
[12]Modified from González-Vega et al. (2013).
[13]Bohlke et al. (2005).
[14]Merriman et al. (2016b).
[15]González-Vega et al. (2015a).

ingredients of animal origin is increased by use of phytase (González-Vega et al., 2015b; Merriman et al., 2016b; Lee et al., 2019b) if they are included in diets containing phytate. In contrast, digestibility of Ca in DCP and MCP is not affected by use of phytase (González-Vega et al., 2015b; Lee et al., 2019b). Digestibility of P in DCP and MCP is also not affected by phytase (Lopez et al., 2022).

From a practical perspective, the digestibility of Ca in limestone is by far the most important because the majority of Ca in commercial diets for pigs usually comes from limestone. As an example, in a corn-soybean meal diet for growing pigs (25 to 50 kg) that is formulated to contain 0.66% Ca, only 17% of the total Ca is from corn and soybean meal, 38% is from DCP, and 45% is from limestone (Figure 4). However, if 500 units of microbial phytase are added to this diet, no DCP need to be used, whereas limestone contribution to the total Ca in the diet increases to 67%. As a consequence, a correct estimation of the digestibility of Ca in limestone is very important for a correct provision of digestible Ca in the diet. Although the STTD of Ca may vary among sources (Lee et al., 2019b), differences in the STTD of Ca among sources of limestone produced in the United States tend to be moderate. It is, however, not known if limestone from other geographies has digestibility of Ca that is similar to the STTD of Ca in limestone from the U.S. It is also not known if the solubility of limestone impacts the STTD of Ca, but particle size does not appear to affect the STTD of Ca or growth performance of pigs (Merriman and Stein, 2016).

Digestibility of Ca by Gestating Sows

Most values for the STTD of Ca were determined in ingredients fed to growing pigs, but the ATTD and STTD of Ca in growing pigs are greater than in sows (Figure 5; Kemme et al., 1997; Lee et al., 2021). It is not likely that differences

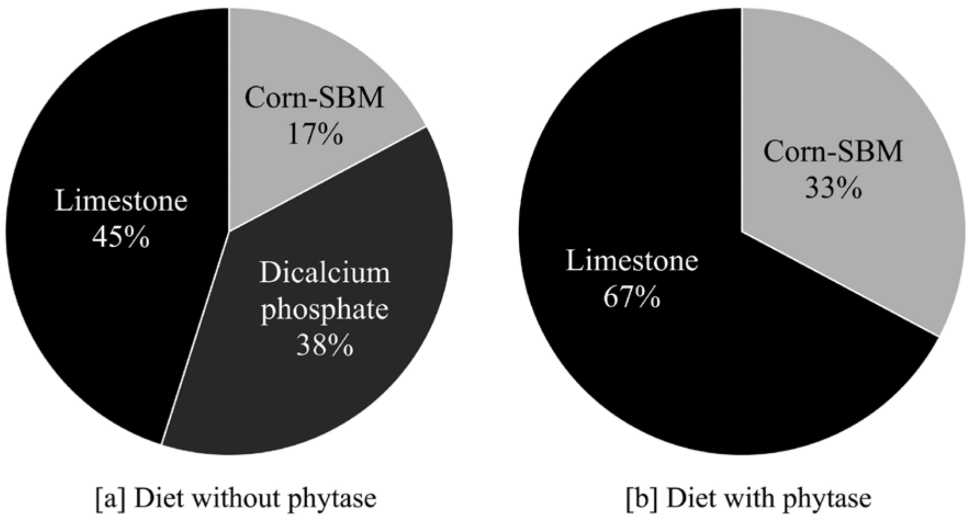

Figure 4. Proportional contribution of Ca by feed ingredients to Ca in complete diets without phytase (a) and with phytase (b), digestible-Ca basis.

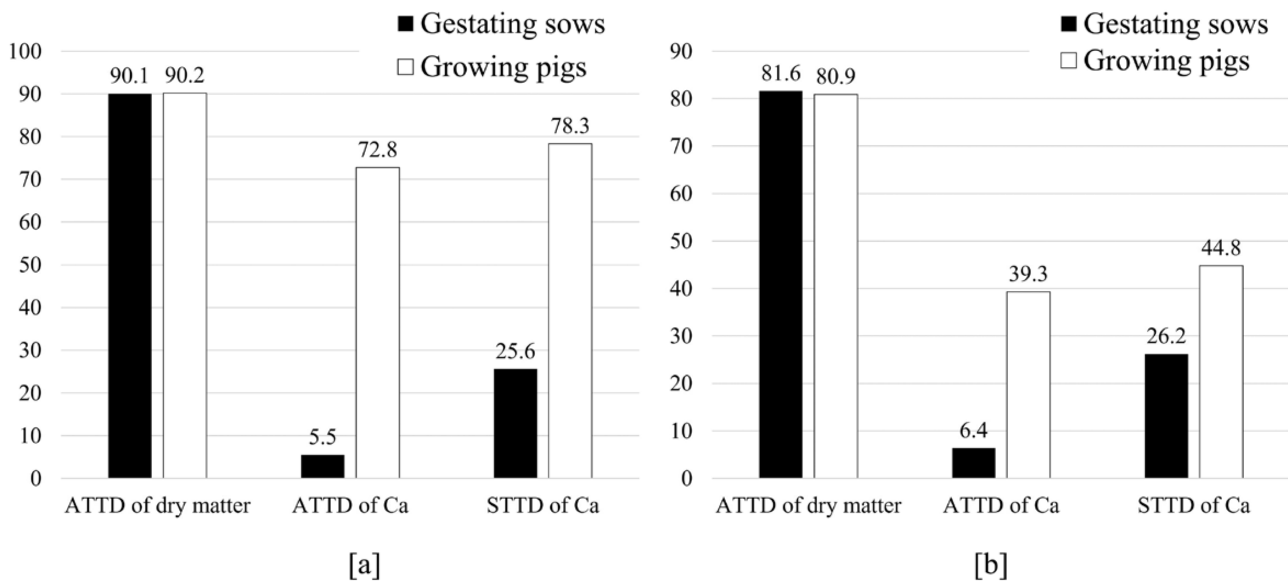

Figure 5. Apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of Ca by growing pigs and sows in mid-gestation fed normal- (a) or high-phytate diets (b). The normal-phytate diets contained corn, soybean meal, limestone, and dicalcium phosphate; the high-phytate diets contained corn, soybean meal, full-fat rice bran, limestone, and dicalcium phosphate (adapted from Lee et al., 2021).

in the level of feed intake is the main reason for these differences because feed intake of sows does not affect digestibility of Ca (Lee et al., 2018a). Basal endogenous losses of Ca (g/kg DMI) from gestating sows are more than 3 times greater than from growing pigs (Bikker et al., 2017; Lee et al., 2021), which is one of the reasons for the lower ATTD of Ca in gestating sows than in growing pigs. However, values for STTD of Ca in gestating sows are much less than in growing pigs, even if values are corrected for the greater basal endogenous losses (Lee et al., 2021). Sows in early gestation need Ca close to the maintenance requirement whereas growing pigs need Ca for both maintenance and tissue and bone development (Bikker and Blok, 2017), which may be the reason for the greater digestibility in growing pigs. Therefore, less Ca relative to intake is retained by sows in early-, mid-, or late-gestation (Everts et al., 1998; Darriet et al., 2017) compared with growing pigs.

Sows in mid- or late- gestation have reduced ATTD of Ca compared with lactating sows (Kemme et al., 1997; Jongbloed et al., 2004; Männer and Simon, 2006; Nyachoti et al., 2006). Likewise, the ATTD and STTD of Ca are reduced in mid-gestation compared with late-gestation (Kemme et al., 1997; Jongbloed et al., 2004, 2013; Nyachoti et al., 2006; Lee et al., 2019a). It is possible that the changing needs for Ca throughout gestation results in changed digestibility because very little Ca is needed for fetus development by sows in early- or mid-gestation compared with sows in late-gestation (Bikker and Blok, 2017).

First parity sows are expected to retain more dietary Ca in the body compared with multiparous sows because of maternal growth, but limited data are available to quantify these effects. Based on computer models, it was proposed that more Ca relative to body size needs to be retained in first parity sows compared with second or third parity sows (Everts et al., 1998), and Bikker and Blok (2017) suggested different Ca requirements for gestating and lactating sows in different parities. Because of the differences between growing pigs and sows, it is not possible to use values for the STTD of Ca obtained in growing pigs and apply them to sows. Due to differences between gestating and lactating sows (Kemme et al., 1997), it likely also will be necessary to determine digestibility values in lactating sows. There is, therefore, a need for conducting research with both gestating and lactating sows to determine digestibility of Ca in commonly used feed ingredients.

Requirements for Digestible Ca

At the time of publication of the current Swine NRC (2012), there were no data for the digestibility of Ca in feed ingredients fed to pigs. Therefore, requirements by NRC (2012) are expressed as requirements for total Ca, although it was acknowledged that requirements based on digestible Ca would be more accurate (NRC, 2012). The majority of Ca and P is stored in bone tissue that has a constant Ca to P ratio, and the requirement for total Ca by growing pigs was, therefore, estimated by multiplying the STTD P requirement by 2.15 (NRC, 2012). However, because STTD values for Ca in most Ca-containing feed ingredients have been generated since publication of the NRC (2012), studies have been conducted in recent years to determine requirements for digestible Ca in diets for growing pigs (González-Vega et al., 2015b, 2016b; Merriman et al., 2017; Lagos et al., 2019a, 2019b). Results from these studies clearly indicated that there are detrimental effects on growth performance of providing excess dietary Ca to growing pigs. This is particularly true if the concentration of STTD P is at or below the requirement, whereas pigs may tolerate excess Ca if P is provided above the requirement. This observation highlights the importance of using the ratio between STTD Ca and STTD P to formulate diets for growing pigs (Lagos et al., 2021b). Summarized data from these experiments also demonstrated that there are linear correlations between body weight of growing-finishing pigs and digestible Ca to digestible P ratios needed to maximize growth or bone ash (Table 7). The ratio between STTD Ca and STTD P that is needed to maximize growth performance decreases as pigs get older, whereas the ratio needed to maximize bone ash increases as pigs increase body weight from 11 to 130 kg. The reason for these changes in the required ratios between STTD Ca and STTD P is likely that growth of bone tissue and growth of soft tissue is not constant throughout the growing-finishing period of pigs (Lautrou et al., 2021). In finishing pigs where

Table 7. Requirements for standardized total tract digestible (STTD) Ca and STTD P to maximize growth performance (average daily gain) or bone ash (grams per femur) by growing-finishing pig[1]

Item	Weight, kg				
	11-25	25-50	50-75	75-100	100-135
STTD P[2], %:	0.33	0.31	0.27	0.24	0.21
Growth performance[3]					
STTD Ca, %	0.47	0.41	0.34	0.29	0.23
STTD Ca to STTD P ratio	1.39	1.31	1.26	1.19	1.10
Bone ash[4]					
STTD Ca, %	0.55	0.55	0.54	0.52	0.49
STTD Ca to STTD P ratio	1.67	1.81	2.00	2.15	2.33

[1]Estimates were calculated from published data (González-Vega et al., 2016a, 2016b; Merriman et al., 2017; Lagos et al., 2019a, 2019b).
[2]Requirements for STTD P are from NRC (2012).
[3]There was a negative linear correlation between body weight (X) of growing-finishing pigs and STTD Ca:STTD P ratios (Y) to maximize growth: $Y = -0.0031X + 1.46$.
[4]There was a positive linear correlation between body weight (X) of growing-finishing pigs and STTD Ca:STTD P ratios (Y) to maximize bone ash: $Y = 0.0063X + 1.58$.

daily protein synthesis is low, the ratio between STTD Ca and STTD P that is needed to maximize bone ash is close to the ratio in actual bone ash because the majority of both Ca and P is used for bone ash synthesis. However, during the growing period when pigs have larger protein synthesis, a greater proportion of dietary P is used for soft tissue synthesis, which results in a lower STTD Ca:STTD P ratio needed to maximize bone ash. The practical implication of these observations is that terminal pigs should be fed diets during the growing-finishing period that have STTD Ca:STTD P ratios that maximize daily gain because it is not necessary to maximize bone ash in terminal pigs (NRC, 2012). In contrast, when feeding developing gilts or intact boars that are intended to be kept for breeding, diets that have STTD Ca:STTD P ratios that maximize bone ash should be fed. To avoid the strong negative impact of these ratios on growth performance it is recommended that P inclusion in these diets is at least 10 to 15% greater than what is required to maximize growth of pigs.

The reason the estimated ratios (i.e., STTD Ca:STTD P ratios between 1.10:1 and 1.40:1) to maximize growth performance generally are in the same range as previously estimated ratios for total Ca to total P likely is that Ca and P in many mixed diets have the same digestibility. As an example, the STTD of Ca in a corn-soybean meal diet supplemented with limestone and calcium phosphate is around 70%, which is also the case for the STTD of P. As a consequence, for a corn-soybean meal diet without phytase, the ratio between Ca and P required to maximize growth performance calculated on a total basis is the same as the ratio calculated on an STTD basis. However, if other ingredients with different digestibility of P or Ca are used or if microbial phytase is included in the diet, required ratios for STTD Ca to STTD P required to maximize growth performance will change and no longer be similar to ratios for total Ca to total P.

Because of the linear reduction in the digestibility of P that is caused by increasing concentrations of dietary Ca (Stein et al., 2011), excess Ca in diets for pigs may result in deficiency of P, which is associated with reduced feed intake (Sørensen et al., 2018). Indeed, regardless of the concentration of dietary P, a linear decrease in average daily feed intake of pigs was observed as dietary Ca increased in diets for pigs from 50 to 85 kg or from 100 to 130 kg (Merriman et al., 2017; Lagos et al., 2019a). Using equations for the correlation between dietary Ca and average daily feed intake from 50 to 85 kg and 100 to 130 kg pigs, it was calculated that inclusion of 0.20 percentage units more Ca than required results in a reduced average daily feed intake of 77 to 241 g. A reduction of feed intake of this magnitude results in a reduction of average daily gain of 50 to 100 g emphasizing the large negative impact of oversupplying Ca in the diets. The negative impact of excess dietary Ca on growth performance of younger pigs is also well documented (Wu et al., 2018; Lagos et al., 2019a). The fact that commercial diets from the swine feed industry contain around 0.20 percentage units more Ca than formulated (Walk, 2016; Lagos et al., 2023) indicates that growth performance of pigs fed commercial diets may be compromised by excess Ca in the diets. Therefore, more attention needs to be given to the concentration of Ca in feed ingredients and complete diets, which involves frequent analysis of Ca in all Ca-containing feed ingredients, including all premixes, as well as analysis of manufactured diets to confirm that diets contain formulated levels of Ca.

Calcium in Diets for Weanling Pigs

After weaning, pigs may be unable to produce enough hydrochloric acid in the stomach to maintain optimum pH, which results in greater gastric pH than required for optimum pepsin activity (Ravindran and Kornegay, 1993). Dietary protein digestion is reduced if pepsin activity is reduced and in most cases, undigested protein in the hindgut of weanling pigs results in diarrhea and increased mortality (Kil and Stein, 2010). Therefore, it is important to maintain an acidic gastric environment for efficient digestion and a healthy gastrointestinal tract, but because limestone has a high acid binding capacity (i.e., buffering capacity; Stas et al., 2022) it has been hypothesized that limestone may increase gastric pH and further reduce the activity of pepsin (Lawlor et al., 2005; Wang et al., 2023). However, in recent experiments, diets that contained only 50% of the requirement for Ca and P failed to reduce gastric pH, and it therefore appears that the negative effects of limestone on gastric pH are less than previously thought (Lagos et al., 2021a, 2021c). In contrast, recent data indicated that increasing phytase in diets fed to newly weaned pigs tended to reduce gastric pH and reduced diarrhea in pigs (Lee et al., 2018b; Lagos et al., 2021a, 2021c). Specifically, it appears that if 2,000 units of phytase is used, not only gastric pH and diarrhea were reduced, but growth performance was also improved compared with pigs fed a control diet without phytase (Lagos et al., 2021a). It is possible that these effects are associated with increased absorption of inositol in pigs fed diets with high concentrations of phytase, because pigs fed diets with phytase were able to maintain pre-weaning levels of plasma inositol whereas pigs fed diets without phytase had a remarkable reduction of plasma inositol after weaning (Lagos et al., 2021a). However, more research is needed to determine the impacts of phytase on Ca, P, and inositol status of newly weaned pigs and at present, the requirement for digestible Ca by pigs from 5 to 11 kg has not been determined.

Conclusion

Values for STTD of Ca are additive in mixed diets for pigs and use of STTD values, therefore, results in the most accurate diet formulations. Values for the STTD of Ca in most commercially used feed ingredients fed to growing pigs have been determined, and addition of microbial phytase to diets increases STTD of Ca. It is, therefore, necessary to use different values for STTD of Ca in diets without phytase than in diets with microbial phytase. Because of the relationship between Ca and P in the intestinal tract of pigs as well as the constant Ca:P ratio in bone tissue, it is necessary that diets are formulated based on a ratio between STTD Ca and STTD P, and requirements for ratios needed to maximize growth performance of growing-finishing pigs have been published. Maximum growth performance is, however, only obtained if the concentration of Ca does not exceed formulated levels because excess dietary Ca is detrimental to P digestibility and growth performance of pigs.

In practical diet formulation, values for the STTD of Ca and P obtained in growing pigs are also applied to sows, but gestating sows have reduced digestibility and retention of Ca and P compared with growing pigs. Future work, therefore, needs to focus on determining digestibility of Ca and P in gestating and lactating sows, and responses to microbial phytase in sows need to be quantified as well.

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Conflict of Interest Statement

L.A.M. is an employee at AB Vista, Marlborough, UK, a global supplier of feed additives including microbial phytase. S.A.L, L.V.L, and H.H.S. have no conflicts of interest.

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