Estimates of Requirements for Digestible Ca by Growing Pigs

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Summary

The standardized total tract digestibility (STTD) of Ca in all major feed ingredients used in diets for pigs has been determined and the positive impact of microbial phytase on STTD of Ca has also been demonstrated. The requirement for STTD Ca by all groups of growing-finishing pigs has also been reported and it is, therefore, possible to formulate diets for growing-finishing pigs, either without or with microbial phytase, based on values for STTD Ca rather than total Ca. Because of the tight relationship between the needs for STTD Ca and STTD P, it is likely that the ratio between STTD Ca and STTD P is more important than the absolute values, but values for the ratio needed to maximize growth performance changes during the growing-finishing period. To maximize growth performance of 11 to 25 kg pigs, a ratio between STTD Ca and STTD P of less than 1.39:1 is required, whereas a ratio of less than 1.10:1 is required for pigs from 100 to 130 kg. However, to maximize bone ash in pigs, greater ratios are needed. In conclusion, results of research published over the last decade have provided information needed to formulate diets for growing-finishing pigs based on requirements for STTD Ca.

Introduction

Current requirements for Ca in diets for growing pigs are based on requirements for total Ca whereas requirements for P are expressed as the requirement for standardized total tract digestibility (**STTD**) of P (NRC, 2012). The reason for this difference is that at the time the NRC (2012) requirements were established, no values for the STTD of Ca in feed ingredients used in diets for pigs were available. However, because of differences in digestibility of Ca among feed ingredients it was acknowledged that the accuracy of diet formulation would be improved if diets could be formulated based on STTD of Ca rather than total Ca (NRC, 2012). As a consequence, over the last decade, values for the STTD of Ca by growing pigs in most of the commonly used feed ingredients have been published and it is, therefore, now possible to formulate diets based on STTD Ca rather than total Ca. The widespread use of microbial phytase in diets for pigs has increased the need for formulation of diets based on STTD Ca rather than total Ca because phytase in addition to releasing P also releases Ca from phytate, and therefore, increases the STTD of Ca (Gonzalez-Vega et al., 2013; 2015a; 2015b; Lagos et al., 2022). Microbial phytase also reduces the endogenous losses of Ca from pigs by preventing binding of endogenous Ca to phytate (Lee et al., 2019a), which further increases the STTD of Ca, and therefore, increases the need for formulating diets based on STTD Ca rather than total Ca.

Severe negative effects of excess Ca in diets for growing pigs have been demonstrated repeatedly (Gonzalez-Vega et al., 2016a; 2016b; Merriman et al., 2017; Lagos et al., 2019a; 2019b). It is likely that the negative effects of Ca are partly a result of binding of Ca to P in the digestive tract of pigs resulting in formation of un-digestible Ca-P complexes, which reduces digestibility of P. As a consequence, excess dietary Ca may create a P-deficiency even if the required concentration of digestible P is included in the diet (Stein et al., 2011; Lee et al., 2020). Unfortunately, commercial diets for pigs in the United States on average contain almost 0.20% more Ca than believed by formulating nutritionists (Lagos et al., 2023), which is likely due to a lack of knowledge about the concentration of Ca in all ingredients in the diets. An excess of 0.20% Ca will likely result in a reduction of average daily gain of at least 50 to 60 grams per day (Merriman et al., 2017). To avoid excess Ca in diets, it is necessary that the concentration of Ca in all feed ingredients, including all feed additives, in the diets is known when diets are formulated and control programs to confirm that final complete diets are produced without excess Ca need to be implemented. In addition, formulation of diets based on STTD Ca will further improve the accuracy of diet formulation because differences in Ca digestibility among ingredients can be taken into account and the impact of microbial phytase on STTD of Ca can be accounted for in the formulation. As a consequence, it may be beneficial to formulate diets based on values for STTD Ca rather than total Ca. The current contribution will attempt to review recent literature on STTD and requirements for STTD by growing-finishing pigs.

Digestibility of Ca

Calcium is digested and absorbed in the stomach and small intestine of pigs and there appears to be no or very limited absorption of calcium in the large intestine (Gonzalez-Vega et al., 2014), but because it is easier to estimate total tract digestibility than ileal digestibility, digestibility of Ca is usually measured over the entire intestinal tract. However, due to the secretion of endogenous Ca into the intestinal tract (Gonzalez-Vega et al., 2013; Nelson et al., 2022), values for apparent total tract digestibility of Ca need to be corrected for endogenous losses of Ca, which results in calculation of values for STTD of Ca. Thus, measurements and calculation of STTD of Ca are identical to the procedures used to determine STTD of P (NRC, 2012). The STTD of Ca in most Ca-containing feed ingredients of animal or plant origin has been reported (Table 1; Gonzalez-Vega et al., 2013; 2015a; 2015b; Merriman et al., 2016b; Zhang et al., 2016). Likewise, values for the STTD of Ca in limestone, monocalcium phosphate, and dicalcium phosphate are available (Gonzalez-Vega et al., 2015a; Merriman and Stein, 2016; Kwon and Kim, 2017; Zhang et al., 2016; Zhang and Adeola, 2017; Lee et al., 2019b). There are, however, only few values for the digestibility of Ca in cereal grains and cereal grain co-products (Bohlke et al., 2005), but due to the very low concentrations of Ca in these ingredients, this is of limited practical importance. In most practical diets, at least 50% of the Ca is from limestone/calcium carbonate and in diets that contain microbial phytase, limestone may account for more than 75% of all the Ca in the diets. Limestone is, therefore, the most important ingredient when it comes to determining Ca digestibility. The STTD of Ca in calcium carbonate has been determined in several experiments and although small differences among sources of calcium carbonate have been report-

Table 1. Standardized total tract digestibility (STTD) by growing pigs of Ca in feed ingredients without and with microbial phytase.

Item, %	STTD of Ca	
Supplementation with phytase[1]	-	+
Mineral supplements		
Monocalcium phosphate[2]	86	86
Dicalcium phosphate[2, 3, 4]	80	80
Ca carbonate[2, 3, 4, 5, 6, 7, 8, 9, 10]	73	78
Plant feed ingredients		
Canola meal[8, 9, 11]	42	65
Soybean meal[8, 9, 12]	78	-
Sunflower meal[9]	26	-
Animal feed ingredients		
Meat and bone meal[13]	77	82
Meat meal[13]	77	86
Fish meal[14]	65	73
Poultry meal[13]	82	82
Poultry by product meal[13]	88	88
Skim milk powder[8]	97	-
Whey powder[8]	99	-
Whey permeate[8]	90	-

[1] Phytase level varied from 500 to 1,500 phytase units/kg diet.
[2] González-Vega et al. (2015b).
[3] Zhang and Adeola (2017).
[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] González-Vega et al., 2013.
[12] Bohlke et al. (2005).
[13] Merriman et al. (2016b).
[14] González-Vega et al., 2015a.

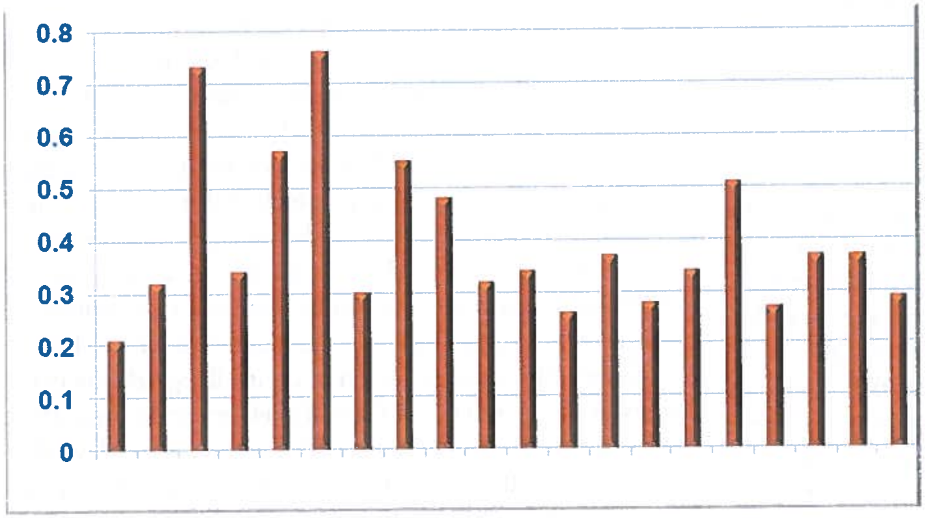

Figure 1. Variation in concentration of Ca among 20 sources of soybean meal (Sotak et al., 2016).

ed (Lee et al., 2019b; Nelson, 2023), the STTD of Ca in calcium carbonate usually is between 65 and 75% (Gonzalez-Vega et al., 2015a; Merriman and Stein, 2016; McGhee and Stein, 2019; Lee et al., 2019b; Nelson, 2023). Some plant ingredients including soybean meal, bakery meal, and distillers dried grains with solubles have large variations in Ca concentrations (Fig. 1; Pedersen et al., 2007; Sotak-Peper et al., 2016; Liu et al., 2018), but the reason for these variations is that calcium carbonate is sometimes added to these ingredients as a flow agent. The actual concentration of calcium carbonate in diets for pigs, therefore, often is greater than indicated only by the inclusion of calcium carbonate or limestone in the formulation.

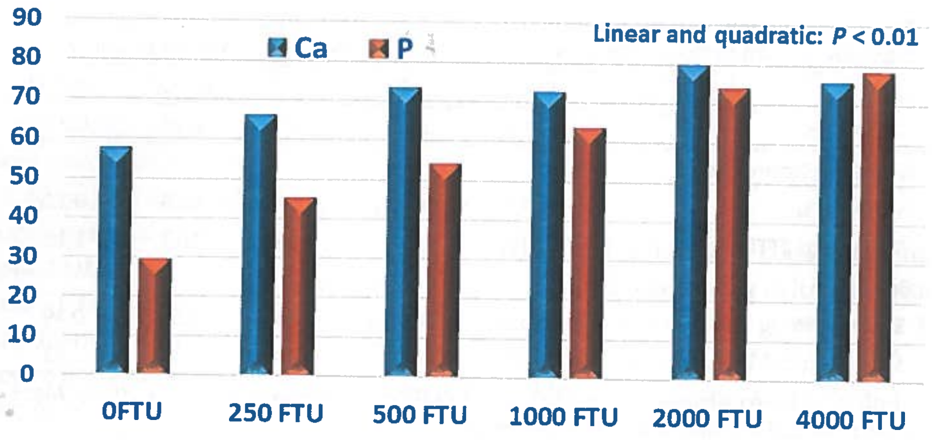

Figure 2. Impact of microbial phytase on digestibility of Ca and P by growing pigs (Lagos et al., 2022).

Effect of Microbial Phytase on Ca Digestibility

Early work with microbial phytase demonstrated that phytase does not only increase the digestibility of P, but also the digestibility of Ca. The reason for this effect is that Ca and other divalent cations can bind to the negative charges on the P groups in phytate, but as microbial phytase hydrolyzes the ester bonds that connect P to the inositol ring in phytase, the cations attached to P will be released when P is released. Because microbial phytase is included in the majority of practical diets for pigs, effects of microbial phytase on the digestibility of Ca, therefore, needs to be taken into account in diet formulation. However, although it is acknowledged that microbial phytase increases the digestibility of Ca (Gonzalez-Vega et al., 2015a; 2015b; Lagos et al., 2022), quantitative effects of microbial phytase on the digestibility of Ca are not well understood, and the increase in STTD of Ca in a feed ingredient that is realized by increasing levels of dietary phytase has not been quantified for all phytases. The impact of phytase on Ca digestibility of plant feed ingredients is a combination of release of indigenous Ca from phytate, prevention of binding of Ca from limestone and animal proteins to phytate, and reduced endogenous losses of Ca (Gonzalez-Vega et al., 2013; 2015b; Lee et al., 2019a; Nelson et al., 2022). Because the number of Ca ions relative to P ions that are liberated from phytate changes as the dose of phytase increases, there is no easy way to predict the impact of phytase on Ca digestibility. The first P ion that is released from phytate will result in release of two Ca ions because Ca is a divalent ion, but for each subsequent release of P, only one Ca will be released and if phytate is completely hydrolyzed, no Ca ions will be released when the last one or two P ions are released. As a consequence, the ratio of released Ca to released P changes with the concentration and effectiveness of phytase being used (Table 2), which in turn results in different increases in digestibility of Ca and P as more phytase is added to the diets (Fig. 2; Lagos et al., 2022). In addition, because the number of Ca ions that are bound to P is affected by the presence of other divalent cations in the diet, including Zn and Mg, the release of Ca is not constant among different types of diets. As an example, if dietary Zn is increased, the impact of microbial phytase on Ca digestibility is reduced (Blavi et al., 2017) presumably because Zn occupies some of the binding sites in the phytate molecule, and therefore, prevents Ca from binding. However, currently, there is a lack of information about the release of different cations by phytase and the impact of increasing levels of phytase in the diets on Ca digestibility is not well understood.

Table 2. Theoretical release of Ca from phytate by microbial phytase[1]

P ions released	Ca ions released	Ca:P ratio of released Ca and P
1	2	2.00:1
2	1	1.50:1
3	1	1.33:1
4	1	1.25:1
5	0	1.00:1
6	0	0.83:1

[1] Assuming there are a total of 5 Ca and 6 P bound to phytate.

The Role of Vitamin D in Ca Digestibility

Absorption of Ca from the lumen of the small intestine occurs through Ca channels that are located on the luminal side of the enterocytes that line the villi in the small intestine. After absorption into the enterocytes, transport proteins aid in the transfer of Ca to the basolateral side of the enterocytes, where a sodium dependent active transporter will transfer the Ca ion to the interstitium before transport to the liver via the hepatic portal vein. At low concentrations of Ca in the diets, the efficiency of Ca absorption is

Table 3. Requirements for standardized total tract digestible (STTD) Ca and STTD P to maximize growth performance (average daily gain) or bone ash 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	0.56	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) needed to maximize average daily gain: $Y = -0.0031X + 1.46$.

[4] There was a positive linear correlation between body weight (X) of growing-finishing pigs and STTD Ca:STTD P ratios (Y) needed to maximize bone ash: $Y = 0.0063X + 1.58$.

increased by binding of $1,25\text{-(OH)}_2\ \text{D}_3$, which is the active form of vitamin D, to vitamin D receptors located on the enterocytes, resulting in increased expression of Ca channel proteins and Ca transport proteins (Gonzalez-Vega et al., 2016b). However, at greater concentrations of Ca in the diets, the tight junctions between enterocytes become selectively permeable allowing for Ca to be absorbed not only via the Ca channels in the enterocytes, but also via paracellular transport of Ca from the intestinal lumen to the interstitium (Lagos et al., 2019b). Because vitamin D is supplied to swine diets in the form of un-hydroxylated vitamin D_3, pigs need to hydroxylate vitamin D at the 1 and at the 25 positions, which takes place in the kidneys and the liver, respectively, to generate the active form of the vitamin, which is $1,25\text{-(OH)}_2\ \text{D}_3$. It is believed that pigs are efficient in this conversion, but recent data from experiments with gestating sows indicated that the STTD of both Ca and P is increased if metabolites of vitamin D_3, in the form of either 1-OH-D_3 or 25-OH-D_3, is supplied in the diets (Lee and Stein, 2022; Lee et al., 2022). In subsequent experiments, it was confirmed that the digestibility of Ca and P also is increased in growing pigs if one of the vitamin D_3 metabolites is added to the diets (Univ. Illinois, unpublished). Because vitamin D_3 and vitamin D_3 metabolites increase Ca absorption, whereas microbial phytase increases the number of Ca ions that are available for absorption, effects of vitamin D_3 metabolites and microbial phytase are additive. However, additional research is needed to fully understand the impacts of vitamin D_3 metabolites on Ca absorption and to determine why un-hydroxylated vitamin D_3 appears to be less efficient in aiding in absorption of Ca and P than a hydroxylated metabolite of vitamin D_3.

Requirements for Digestible Ca

The majority of Ca in the body of pigs is stored in bones and to synthesize bone tissue, both Ca and P are needed along with a protein matrix. Although a number of other minerals are also needed in the synthesis of bone tissue, Ca is quantitatively the most important mineral and constitutes around 38% of bone ash whereas P is present at around 17% (Lagos et al., 2019a; 2019b). Because of these rather constant concentrations of Ca and P in bone tissue, the ratio between Ca and P is fixed and does not change regardless of provisions of Ca and P in the diets. As a consequence, if either Ca or P is deficient in the diet, pigs will synthesize less bone ash, meaning that the bones will become smaller, but still with the same Ca to P ratio (Gonzalez-Vega et al., 2016b; Merriman et al., 2017; Lagos et al., 2019a; 2019b). It is, therefore, important that the ratio between Ca and P in diets for growing pigs meets the need for synthesis of bone tissue. However, whereas Ca is primarily used in bone tissue synthesis, P is also used in the synthesis of soft tissues and other compounds in the body, but as pigs grow older, the proportion of absorbed P used for bone tissue synthesis increases relative to the proportion used for soft tissue synthesis. In finishing pigs, the dietary ratio between Ca and P needed to maximize bone ash closely resembles the ratio between the two minerals in bone ash whereas in smaller pigs, a lower ratio between Ca and P is needed to maximize bone ash because a larger proportion of the absorbed P is used in soft tissue synthesis. To maximize bone ash in growing finishing pigs, the ratio between Ca and P, therefore, is linearly increased from 11 to 130 kg (Table 3). However, dietary concentrations of Ca and P needed to maximize bone ash are greater than the concentrations needed to maximize growth performance (NRC, 2012). Likewise, the ratios between STTD Ca and STTD P needed to maximize growth performance are different from those needed to maximize bone ash. Because of the strong negative effects of excess dietary Ca on growth performance, the ratios between STTD Ca and STTD P that are needed to maximize growth performance are maximum ratios that should not be exceeded. The ratio between STTD Ca and STTD P needed to maximize growth performance of pigs between 11 and 25 kg does not exceed 1.39:1, but this ratio gradually decreases as pigs become heavier, and for pigs between 100 and 130 kg, the ratio should not exceed 1.10:1 (Table 3). These ratios were developed in experiments where pigs were fed multiple levels of both Ca and P and the negative effects of exceeding the suggested ratios were clearly demonstrated (Gonzalez-Vega et al., 2016b; Merriman et al., 2017; Lagos et al., 2019a; 2019b). Later, these ratios were validated in an experiment with pigs fed the suggested ratios from 11 kg to market weight and it was confirmed that pig performance is maximized if these ratios are met, but not exceeded (Lagos et al., 2021). Results of the experiments conducted to determine requirements for STTD Ca also confirmed that the requirements for STTD P suggested by NRC (2012) are adequate to maximize growth performance of terminal pigs if Ca is not provided in excess of the suggested ratios.

Because of the different ratios between STTD Ca and STTD P needed to maximize growth performance and bone ash, it is suggested that the ratios needed to maximize growth performance is used for terminal pigs whereas the ratios needed to maximize bone ash are used in diets for developing gilts that are intended to be kept for reproduction. However, due to the negative effect of excess Ca on the STTD of P, it is also suggested that the provision of P in diets for developing gilts is at least 10% greater than in diets for terminal pigs, and therefore, 10% greater than NRC (2012) requirements. The advantage of formulating diets based on values for STTD Ca rather than values for total Ca is that differences in STTD among feed ingredients can be taken into account and effects of microbial phytase on digestibility of Ca is also accounted for.

Conclusion

Diets for growing-finishing pigs can be formulated based on values for STTD Ca rather than total Ca because values for STTD of Ca in most Ca containing ingredients have been reported. It is also recognized that both microbial phytase and two metabolites of vitamin D increase STTD of Ca, and effects of phytase and vitamin D metabolites are additive. Excess Ca is negative for growth performance of pigs, and diets should, therefore, be formulated based on a ratio between STTD Ca and STTD P and the ratio between STTD Ca and STTD P is more important than the actual concentration of the two minerals in the diets. Requirements for STTD P suggested by NRC (2012) are accurate if Ca is not fed in excess of requirements. If STTD P is at the requirement, growth performance of growing finishing pigs between 11 kg and market weight is maximized if the ratio between STTD Ca and STTD P is gradually reduced from 1.39:1 to 1.10:1. However, for developing gilts, the provision of STTD P should exceed NRC (2012) requirements by at least 10% and the ratio between STTD Ca and STTD P should increase from 1.67:1 in 11 to 25 kg pigs to 2.33:1 in 100 to 130 kg pigs.

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