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Review: Aspects of digestibility and requirements for minerals and vitamin D by growing pigs and sows

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ABSTRACT

Some of the biggest changes in mineral nutrition for pigs that have occurred due to recent research were caused by the understanding that there is a loss of endogenous Ca and P into the intestinal tract of pigs. This resulted in development of the concept of formulating diets based on standardized total tract digestibility (**STTD**) rather than apparent total tract digestibility because the values for STTD of these minerals are additive in mixed diets. There are, however, no recent summaries of research on digestibility and requirements of macro- and microminerals and vitamin D for pigs. Therefore, the objective of this review was to summarize selected results of research conducted over the last few decades to determine the digestibility and requirements of some minerals and vitamin D fed to sows and growing pigs. Benefits of microbial phytase in terms of increasing the digestibility of most minerals have been demonstrated. Negative effects on the growth performance of pigs of over-feeding Ca have also been demonstrated, and frequent analysis of Ca in complete diets and raw materials is, therefore, recommended. There is no evidence that current requirements for vitamin D for weanling or growing-finishing pigs are not accurate, but it is possible that gestating and lactating sows need more vitamin D than currently recommended. Vitamin D analogs and metabolites such as $1(OH)D_3$ and $25(OH)D_3$ have beneficial effects when added to diets for sows in combination with vitamin D_3. Recent research on requirements for macrominerals other than Ca and P is scarce, but it is possible that Mg in diets containing low levels of soybean meal is marginal. Some of the chelated microminerals have increased digestibility compared with sulfate forms, and hydroxylated forms of Cu and Zn appear to be superior to sulfate or oxide forms. Likewise, dicopper oxide and Cu methionine hydroxy analog have a greater positive effect on the growth performance of growing pigs than copper sulfate. The requirement for Mn may need to be increased whereas there appears to be no benefits of providing Fe above current requirements. In conclusion, diets for pigs should be formulated based on values for STTD of Ca and P and there are negative effects of providing excess Ca in diets. It is possible vitamin D analogs and metabolites offer benefits over vitamin D_3 in diets for sows. Likewise, chelated forms of microminerals or chemical forms of minerals other than sulfates or oxides may result in improved pig performance.

Implications

There are no recent summaries of digestibility and requirements estimates for minerals and vitamin D fed to growing and reproducing swine. In the present contribution, the benefits of formulating diets based on standardized total tract digestibility of Ca and P and the negative effects of over-formulation with Ca are highlighted. Effects of using sufficient quantities of microbial phytase to degrade all dietary phytate and increasing digestibility of all minerals are discussed. Advantages of using vitamin D analogs or metabolites in diets for sows are demonstrated, and the use of chelated or other non-sulfate or oxide forms of microminerals are also recommended.

Introduction

Mineral nutrition in pigs has received more attention during recent years than previously for primarily three reasons: (1) Concerns about environmental impacts of mineral use in swine diets have resulted in an increased focus on digestibility and requirements for minerals; (2) The universal availability of microbial phytase has highlighted the importance of formulating diets based on concentrations of digestible Ca and digestible P; and (3) the emergence of new sources of microminerals, including chelated forms,

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has resulted in a renewed interest in defining absorption and functions of microminerals in diets for pigs. As a consequence, much of the research in mineral nutrition for pigs conducted over the last 20 years has focused on the digestibility of minerals and has been related to either microbial phytase or new sources of microminerals. Because of the impact of microbial phytase on digestion, absorption, and metabolism of Ca and P (Arredondo et al., 2019; Dersjant-Li and Dusel, 2019; Mesina et al., 2019; Hu et al., 2022), much research has been conducted to understand digestibility and metabolism of these two minerals with subsequent publication of digestibility values for Ca and P in most commonly used feed ingredients (Almeida and Stein, 2010; 2012; Rojas and Stein, 2012; Sotak-Peper et al., 2016; Stein et al., 2016; Lee et al., 2023a; 2023b). It is, therefore, now possible to formulate diets for pigs based on digestible Ca and digestible P, which in turn has required research to estimate requirements for digestible P [National Research Council (**NRC**), 2012], and for digestible Ca (Gonzalez-Vega et al., 2016a; 2016b; Merriman et al., 2017; Lagos et al., 2019a; 2019b). The impact of microbial phytase on the digestibility of dietary minerals other than Ca and P has also been determined (She et al., 2018a; Arredondo et al., 2019; Lagos et al., 2022), but so far that has not resulted in an interest in formulating diets for pigs based on digestible concentrations of minerals other than Ca and P. Because of the importance of vitamin D on digestion and absorption of Ca and P, recent research has also addressed questions related to the impact of vitamin D and vitamin D analogs and metabolites on digestion and metabolism of minerals and other nutrients in pigs (Weber et al., 2014; Duffy et al., 2018; Lee and Stein, 2022; Lee et al., 2022).

The interest in using chelated microminerals in diets for pigs has resulted in research that has generated data to increase the understanding of micromineral digestion. In addition to chelated microminerals, new chemical forms of minerals such as hydroxylated minerals and dioxide forms have been introduced, which has also contributed to increased knowledge about micromineral nutrition.

With the increased emphasis on the concept of ''digestibility'' of minerals, much less focus than previously has been placed on determining the ''relative bioavailability'' of minerals. Determination of relative bioavailability involves determining the response to feeding one mineral source relative to feeding another source of the same mineral and then calculate the efficiency of the test source in supporting a specific outcome using a slope-ratio method (Lautrou et al., 2021). The reduced use of the relative bioavailability assay is likely a consequence of the fact that relative bioavailability is a concept that primarily is useful when comparing different sources of the same mineral, but it is difficult to use this concept in practical diet formulation or in work to estimate requirements of minerals because the values for relative bioavailability are not always additive in mixed diets. In contrast, digestibility values for minerals easily translate to diet formulation and requirement estimates and if digestibility values are corrected for endogenous losses, they are additive in mixed diets (Almeida and Stein, 2010; NRC, 2012; Lagos et al., 2021b).

The current contribution is a summary of a presentation the author was invited to give at the 19th biannual conference of the Australian Pig Science Association in November, 2023. In line with the invitation, a significant part of the summary is focused on work completed in the author's own laboratory. The objective was to highlight selected results of recent research to determine the digestibility and requirements by pigs of minerals and vitamin D and to provide some overall conclusions from this research. Due to the economic and environmental importance of P in nutrition, a large part of the discussion is centered on P, Ca, and vitamin D, with less emphasis on other macrominerals. Among the microminerals, the majority of recent work has focused on Zn and Cu with less published work on other microminerals and this review will reflect this balance as well. With a few exceptions, only peer-reviewed publications published in the last 20 years are included in this summary. The references used were selected specifically based on their emphasis on digestibility, absorption, and requirement estimates, but it is recognized that many other aspects of mineral nutrition are equally important and could have been included. Likewise, many research groups other than the ones cited in this summary have made valuable contributions to the current understanding of mineral nutrition in pigs. This is particularly true for aspects related to postabsorptive metabolism of minerals, which is not included in this review due to space and time limitations. Thus, the objective of this contribution is not to review all aspects of mineral nutrition, but rather to focus on the specific topics that the author was invited to discuss at the Australian Pig Science Association conference.

Digestibility of phosphorus and requirements for digestible phosphorus

The understanding that not all dietary P is available for use by pigs resulted in determination of the relative bioavailability of P in most feed ingredients and ''available P'' became the standard for requirement estimates (NRC, 1988; 1998). It was, however, demonstrated that values for digestibility of P were more representative of P utilization by pigs than values for relative bioavailability, and values for the total tract digestibility of P were published (Jongbloed and Everts, 1992). The original digestibility values were based on apparent total tract digestibility (**ATTD**) of P without corrections for the endogenous loss of P, but later work demonstrated that a substantial amount of endogenous P is lost from the intestinal tract of pigs (Fan et al., 2001; Letourneau-Montminy et al., 2015; Bikker et al., 2017). It was also realized that because of the endogenous loss of P, values for ATTD of P are not always additive in mixed diets (Fan and Sauer, 2002; Almeida and Stein, 2010; Lautrou et al., 2021). Therefore, values for the true total tract digestibility of P were determined in a number of feed ingredients (Fan et al., 2001; Ajakaiye et al., 2003; Dilger and Adeola, 2006; Pettey et al., 2006). It was later recognized that determination of the basal endogenous loss of P, rather than the total endogenous loss, and subsequent calculation of values for the standardized total tract digestibility (**STTD**) of P, was a more practical way of generating values for diet formulation (Almeida and Stein, 2010; 2012). Values for the STTD of P, unlike values for the ATTD of P, are not impacted by the level of P in the diet and therefore are additive in mixed diets (Kim et al., 2012a; She et al., 2018b). As a consequence, requirements for P based on STTD of P were introduced (NRC, 2012; Bikker and Blok, 2017) and commercial diets for pigs in North America and in many other countries are now formulated based on STTD of P. For growing pigs, the endogenous loss of P that has been measured in a number of experiments has been remarkably consistent and it has, therefore, been suggested that a common value for endogenous loss of P of 190 mg/kg DM intake can be used to correct ATTD values for P to calculate STTD values (NRC, 2012).

Effects of microbial phytase on STTD of P have also been determined, and in most cases, microbial phytase increases the concentration of STTD P in diets by 0.05–0.12 percentage units if the inclusion of phytase is between 500 and 1 500 phytase units per kg diet, depending on diet composition and type of phytase. Responses to phytase are ingredient-specific (Almeida and Stein, 2010; Rojas and Stein, 2012), but in mixed diets, the maximum response on digestibility of P to microbial phytase has most often been obtained with inclusion of between 1 000 and 2 000 phytase units (Almeida et al., 2013; Arredondo et al., 2019; Dersjant-Li and

Dusel, 2019; Mesina et al., 2019; Hong and Kim, 2021). However, results of recent experiments indicate that some of the newer phytases are more efficient in releasing P from phytate than older phytases and the maximum release of P from phytate may be obtained by using between 2 000 and 4 000 units of a newer phytase, which can result in STTD of P of up to around 80% (Espinosa et al., 2022; Lagos et al., 2022; Zhai et al., 2022). Inclusion of elevated levels of microbial phytase in diets for pigs results in total degradation of phytate with a subsequent release and absorption of inositol and increased concentrations of plasma inositol (Lagos et al., 2021a). The implication of increased inositol in plasma is still to be elucidated, but there are indications that plasma inositol is correlated with certain immune parameters (Lagos et al., 2021a). As an example, inositol downregulates interleukin-6 and is also a precursor for phospholipids, which are important for maintaining plasma membranes in the body (Espinola et al., 2021). In addition, a deficiency of inositol results in reduced intestinal immunity in fish (Li et al., 2018).

The majority of work to determine P digestibility in feed ingredients and effects of microbial phytase on P digestibility has been conducted in growing pigs specifically with young growing pigs. Although it is possible that effects of phytase on increasing the digestibility of P may be reduced in finishing pigs compared with weanling or growing pigs (Lagos et al., 2022), the same digestibility values are usually used in formulation of diets for all groups of pigs. Gestating sows, however, have a digestibility of P that is much less than growing pigs (Lee et al., 2018; 2021) and lactating sows have a digestibility of P that is greater than gestating sows (Zhai et al., 2021; Casas et al., 2022). The reduced digestibility of P in gestating sows compared with growing pigs may partly be attributed to the fact that gestating sows have a much greater basal endogenous loss of P than growing pigs (Bikker et al., 2017; Lee et al., 2021). The response to microbial phytase in gestating sows also appears to be less than the response that is usually obtained in growing pigs (Zhai et al., 2021; Lee et al., 2022). More work is, therefore, needed to determine STTD of P in feed ingredients fed to gestating and lactating sows because applying STTD values for P obtained in growing pigs to sows results in inaccuracies in diet formulation (Bikker et al., 2017). Nevertheless, it is recognized that even if STTD values can accurately predict digestibility and absorption of P from the intestinal tract, STTD values do not predict postabsorptive metabolism. As the metabolism of P is affected by the presence of Ca and other minerals in the body, a high STTD of P does not always result in high metabolic utilization.

Recent work to determine requirements for STTD P by weanling and growing pigs (Adeola et al., 2015; Vier et al., 2019a; 2019b) indicated that requirements for STTD P may be greater than currently estimated by NRC (2012). However, in all of these experiments, very wide Ca to P ratios were used, which likely reduced the digestibility of P, and therefore, over-estimated the requirement for P (Stein et al., 2011). Indeed, a negative impact of excess Ca on the estimated requirement for P has been demonstrated (Letourneau-Montminy et al., 2012; Wu et al., 2018) if dietary P does not exceed requirements. In experiments where multiple levels of both Ca and P were used, results indicated that if dietary total Ca does not exceed, the NRC (2012) requirement, average daily gain and gain-to-feed ratios in weanling, growing, and finishing pigs are maximized if STTD P is at NRC (2012) requirements (Gonzalez-Vega et al., 2016b; Merriman et al., 2017; Lagos et al., 2019a; 2019b). Likewise, in a meta-analysis of factors influencing P utilization by growing pigs, it was concluded that increasing dietary Ca had a negative impact on the retention of P and animal weight gain at low dietary P levels, but not if dietary P exceeded the requirement (Letourneau-Montminy et al., 2012).

A novel procedure to estimate the requirements of P in gestating and lactating sows based on measuring urine excretion of P was recently introduced (Grez-Capdeville and Crenshaw, 2022). Although this procedure still needs to be validated, it may represent an easy and inexpensive way to estimate P requirements in sows and possibly also in growing pigs.

Calcium digestibility and requirements for digestible calcium

Because of the low cost of limestone (i.e., calcium carbonate), little attention has been paid to the digestibility of Ca in feed ingredients and Ca requirements have usually been estimated as requirements for total Ca (NRC, 1998; 2012; Philippine Society of Animal Nutritionists, 2010; Rostagno et al., 2017; de Blas et al., 2018). However, because of the negative impact of dietary Ca on the digestibility of P (Fig. 1; Stein et al., 2011; Letourneau-Montminy et al., 2012; Lee et al., 2020; Hu et al., 2022) and because excess dietary Ca has a negative impact on the ability of microbial phytase to release P from phytate (Hu et al., 2022), more attention has been given to Ca digestibility in recent years. Indeed, recent requirement recommendations for Ca were based on STTD Ca to account for differences in the digestibility of Ca among sources (Bikker and Blok, 2017; Centraal Veevoederbureau, 2020).

Calcium is primarily digested and absorbed in the small intestine and digestibility of Ca at the end of the small intestine is not different from the digestibility determined over the entire digestive tract (Gonzalez-Vega et al., 2014; Aderibigbe et al., 2021). However, determination of digestibility values for Ca has been prioritized only in the last decade, but because there is a significant loss of endogenous Ca from the intestinal tract (Gonzalez-Vega et al., 2013; Misiura et al., 2018; Sung et al., 2020), STTD values for Ca need to be calculated to obtain values that are additive in mixed diets. Therefore, the basal endogenous loss of Ca needs to be determined, which may be accomplished using a Ca-free diet (Gonzalez-Vega et al., 2015a; 2015b; Sung et al., 2020). However, unlike values for the basal endogenous loss of P that are constant among experiments (NRC, 2012), there seems to be more variability among experiments in estimates for basal endogenous loss of Ca (Table 1). It is, therefore, recommended that the basal endogenous loss of Ca is determined in each experiment where the STTD of Ca is calculated. However, it has also been suggested that a constant value (250 mg/kg DM intake) for the endogenous loss of Ca can be used to correct values for ATTD of Ca to STTD of Ca (Bikker and Blok, 2017). Likewise, because Ca can chelate to phytate in ingredients of plant origin, values for STTD of Ca are increased if microbial phytase is added to the diets (Gonzalez-Vega et al., 2013; Espinosa et al., 2022; Lagos et al., 2022). However, Ca from limestone may also chelate to phytate in the stomach of pigs after being solubilized, and as a consequence, microbial phytase will increase the STTD of Ca in limestone (Gonzalez-Vega et al., 2015a; Lee et al., 2019b) by preventing solubilized Ca from limestone from binding to phytate. Calcium of endogenous origin

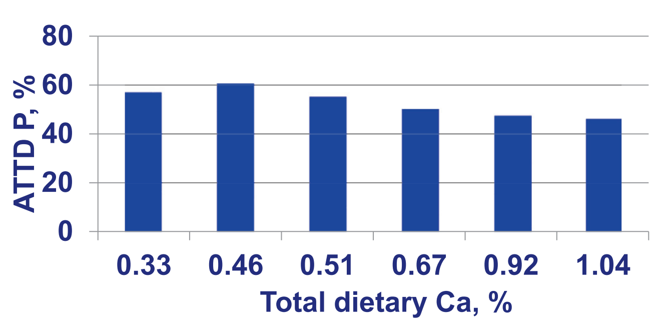

Fig. 1. Impact of dietary total Ca on apparent total tract digestibility (ATTD) of P in growing pigs (source: Stein et al., 2011).

Table 1
Basal endogenous losses of Ca by growing pigs and sows estimated in different experiments[1].

Reference	Initial BW, kg	Basal endogenous loss of Ca, mg/kg DM intake
Growing pigs		
Gonzalez-Vega et al., 2015a	17.7	123
Gonzalez-Vega et al., 2015b	19.4	396
Merriman and Stein, 2016	15.4	329
Blavi et al., 2017	15.4	430
Lee et al., 2019b, Exp. 1	19.0	463
Lee et al., 2019b, Exp. 2	14.9	782
Sung et al., 2020	10.2	659
Lee et al., 2021	19.8	430
Nelson et al., 2022	17.7	512
Average	–	458
Sows		
Lee et al., 2019a, day 13[2]	219.1	1 225
Lee et al., 2019a, day 55[2]	219.1	1 036
Lee et al., 2019a, day 96[2]	219.1	737
Lee et al., 2021, day 44[2]	248.8	1 518
Average	–	1 129

[1] Only values from experiments where pigs were fed corn-based diets without microbial phytase are included.
[2] The day refers to day of gestation when measurements were initiated.

may also chelate with phytate in the stomach, which results in increased endogenous loss of Ca, but inclusion of microbial phytase in the diets reduces the ability of phytate to chelate endogenous Ca and the endogenous loss of Ca from both growing pigs and sows is reduced if phytase is added to the diets (Lee et al., 2019a; Nelson et al., 2022). In contrast, because Ca from monocalcium phosphate and dicalcium phosphate appears not to solubilize in the stomach, there is no impact of microbial phytase on the digestibility of Ca in monocalcium phosphate or dicalcium phosphate (Gonzalez-Vega et al., 2015a; Lee et al., 2019b). It is, therefore, necessary to determine the STTD of Ca in ingredients both without and with microbial phytase because the phytase response is ingredient specific. As is the case for P, the STTD of Ca is often maximized by use of between 1 000 and 2 000 units of microbial phytase (Almeida et al., 2013; Arredondo et al., 2019), but when some newer phytases were used, a linear increase in the STTD of Ca was observed until around 4 000 units of phytase were used (Espinosa et al., 2022; Lagos et al., 2022; Zhai et al., 2022).

Because Ca is a divalent cation, it is chelated to two P units on the phytate molecule. It is, therefore, likely that when the first unit of P is hydrolyzed off phytate, two Ca units are released, but with the hydrolysis of the next three P units, only one Ca is released for each released P, and when the last two units of P are released, no Ca will be released. The implication of this is that at lower concentrations of microbial phytase, where only a few of the P units on each phytate molecule are hydrolyzed, the release of Ca is greater than the release of P, but if greater concentrations of phytase are used and more P is hydrolyzed off phytate, the amounts of P released will be close to the amount of Ca released. Theoretically, if all P is released from phytate, more P than Ca will be released because phytate usually caries 6 units of P and only 5 units of Ca. It is, therefore, not possible to use a constant value for Ca release by phytase because the amount of phytase influences the ratio of Ca to P being released. Nevertheless, values for STTD of Ca in most Ca-containing feed ingredients used in swine nutrition have been determined without and with microbial phytase (Stein et al., 2016; Lee et al., 2023a). Based on these values, it became possible to formulate diets based on STTD Ca. A series of experiments were subsequently conducted to determine requirements for digestible Ca by weanling and growing-finishing pigs (Gonzalez-Vega et al., 2016a; 2016b; Merriman et al., 2017; Lagos et al., 2019a, 2019b). Results of these experiments clearly demonstrated that if STTD P does not exceed the requirement, any amount of excess Ca will reduce growth performance of pigs (Fig. 2; Fig. 3). It was also determined that if STTD of P is greater than the requirement, Ca can also exceed the requirement without detrimental effects on pig growth performance, which is also in agreement with results of a meta-analysis on P utilization by growing pigs (Letourneau-Montminy et al., 2012). Because of this relationship between requirements for digestible Ca and digestible P, it was determined that the requirements for Ca and P are most correctly described as the ratio between STTD Ca and STTD P. For pigs weighing less than 25 kg, the STTD Ca:STTD P ratio needed to maximize growth performance is less than 1.40:1, but this ratio is linearly reduced as pigs get heavier and in pigs greater than 100 kg, the ratio is 1.10:1 or less (Table 2). In contrast, if the objective is to maximize bone ash in pigs, the ratio increases from around 1.65:1 in young pigs to more than 2.10:1 in older pigs. When feeding pigs meant for slaughter, the ratios to optimize growth performance are recommended because there is no need to maximize bone ash in these pigs. However, in diets for developing gilts and boars, the ratios to maximize bone ash should be used, but to avoid reducing growth performance of these pigs, it is recommended to increase the provision of STTD P by at least 20–25% as well. A recent review provides data for both the STTD of Ca in most feed ingredients commonly used in diets for pigs as well as requirements for STTD Ca to maximize growth and bone ash, and also discusses differences in digestibility between growing-finishing pigs and sows (Lee et al., 2023a).

Because of the strong negative effects of overfeeding Ca to pigs, it is critical that diets do not contain more Ca than required. Unfortunately, two recent surveys of commercial diets indicate that diets used in the European Union and in the U.S. contain approximately 0.20% more Ca than formulated (Walk, 2016; Lagos et al., 2023). The reason for this oversupply of Ca most likely is that raw materials are not frequently analyzed for Ca, but Ca concentrations in many raw materials fluctuate considerably. Indeed, large variability in the concentration of Ca among sources of soybean meal, canola meal, 00-rapeseed meal, bakery meal, distillers dried grains with solubles, and rice bran has been reported (Table 3; Maison et al., 2015; Sotak-Peper et al., 2016; Liu et al., 2018; Espinosa et al., 2019c; Fanelli et al., 2023). If ingredients are not frequently analyzed for Ca, this variability is likely not captured in diet formulation (Lagos et al., 2023). Many feed additives used in diets for pigs also use calcium carbonate as a carrier, but this Ca may not always be accounted for in diet formulation, which further contributes to an oversupply of Ca in the diets. It is also likely that because of the low price of limestone, inclusion in the formulation

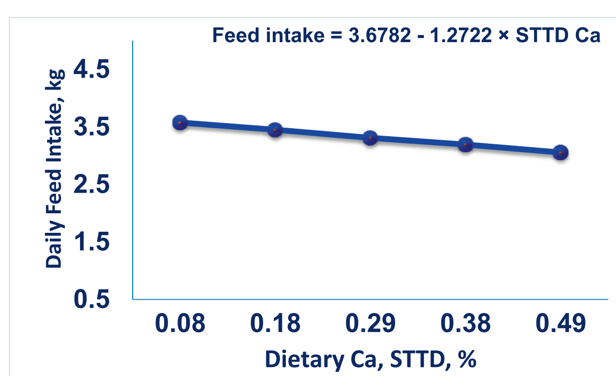

Fig. 2. Impact of dietary standardized total tract digestible (STTD) Ca on average feed intake of pigs from 100 to 130 kg (source: Merriman et al., 2017).

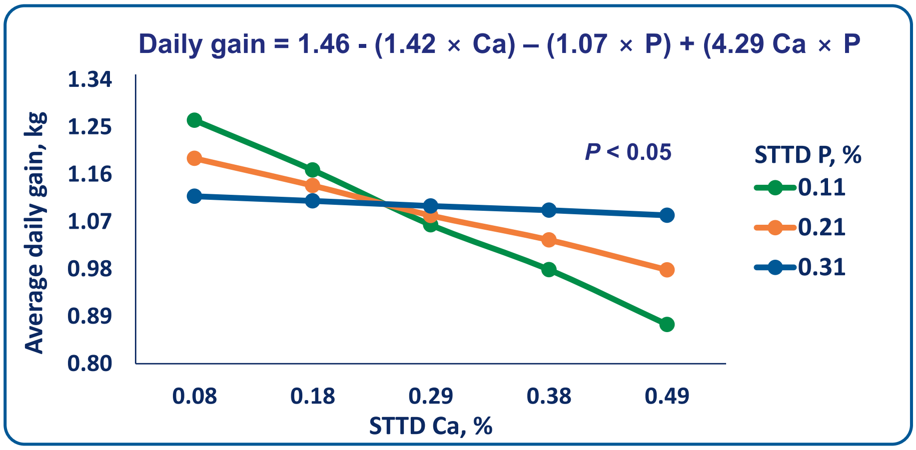

Fig. 3. Impact of standardized total tract digestible (STTD) Ca on average daily weight gain of pigs from 100 to 130 kg fed three different levels of STTD P (source: Merriman et al., 2017).

Table 2
Requirements for standardized total tract digestible (STTD) P and STTD Ca for growing pigs meant for slaughter or growing pigs kept for breeding [1,2,3].

Item	7 – 11 kg	11–25 kg	25–50 kg	50–75 kg	75–100 kg	100–130 kg
Pigs for slaughter						
STTD Ca:STTD P	1.40	1.39	1.31	1.26	1.19	1.10
STTD P, %	0.40	0.33	0.31	0.27	0.24	0.21
STTD Ca, %	0.56	0.46	0.41	0.34	0.29	0.23
Pigs for breeding						
STTD Ca:STTD P	1.60	1.67	1.81	2.0	2.15	2.33
STTD P, %	0.46	0.38	0.36	0.31	0.28	0.24
STTD Ca, %	0.74	0.63	0.65	0.62	0.60	0.56

[1] Requirements for STTD P for pigs kept for slaughter are from NRC (2012).
[2] Requirements for STTD P for pigs kept for breeding were calculated as 1.15 times the requirements for pigs kept for slaughter to prevent the negative impact on growth performance of adding additional Ca to the diets.
[3] Requirements for STTD Ca and STTD Ca:STTD P ratios were calculated from Gonzalez-Vega et al. (2016a; 2016b); Merriman et al. (2017); Lagos et al. (2019a; 2019b).

Table 3
Variation in Ca concentration in some feed ingredients commonly used in diets for pigs.

Ingredient	N	Ca average %	Ca minimum %	Ca maximum, %
Soybean meal[1]	22	0.40	0.24	0.75
Canola meal[2]	5	0.85	0.67	1.21
00-rapeseed meal[2]	8	0.74	0.68	1.21
Bakery meal[3]	46	0.27	0.06	1.34
Distillers dried grains with solubles[4]	8	0.08	0.02	0.34
Rice bran, full fat[5]	18	0.29	0.04	1.61

[1] Sotak-Peper et al. (2016).
[2] Maison et al. (2015).
[3] Liu et al. (2018).
[4] Espinosa et al. (2019c).
[5] Fanelli et al. (2023).

of this ingredient is sometimes more generous than needed, which also contributes to excess Ca in the final diet. Whatever the reason, an oversupply of Ca in diets for growing or finishing pigs of around 0.20% units will result in reduced feed intake and reduced average daily gain of between 50 and 100 g (Lagos et al., 2023). It is possible that the reason excess dietary Ca is so detrimental to the growth of pigs is that, compared with older genotypes, modern pigs have greater muscle growth compared with skeletal growth, which requires less Ca relative to P. It is, therefore, critical that excess of Ca in diets for pigs is avoided and current requirement estimates for Ca by NRC (2012) should be regarded as maximum values. Formulating diets based on a ratio between STTD Ca and STTD P provides the best chances for avoiding overfeeding Ca while maintaining growth performance of pigs and reducing Ca excretion in the urine and feces (Lagos et al., 2021b, 2021c).

Vitamin D and analogues and metabolites of vitamin D

One of the roles of vitamin D is to contribute to the absorption of Ca and P by binding to the vitamin D receptor in the intestine, which results in expression of Ca channel proteins and Ca transport proteins in the enterocytes, thereby allowing increased absorption of Ca and P. There is, therefore, a correlation between vitamin D and digestibility of Ca and P – in particular when Ca and P provisions are low. The requirement for vitamin D_3, which is the form of vitamin D that is included in commercial diets, is estimated at 220 international units per kg of diet in weanling pigs, 200 units in 11–25 kg pigs, and 150 units in growing and finishing pigs (NRC, 2012). These requirement estimates have been unchanged for more than 30 years (NRC, 1988; 1998). In contrast, the requirement for vitamin D_3 in diets for sows was increased from 200 international units in NRC (1998) to 800 international units per kg diet in NRC (2012). The reason for this increase was indications that a greater dose of vitamin D_3 is needed to minimize still born pigs in gilts and sows (Lauridsen et al., 2010). The reduced number of still born pigs from sows fed greater levels of vitamin D_3 may be a consequence of the fact that vitamin D is needed in many reproductive organs where receptors are present and it is, therefore, likely that the effects of vitamin D on reproductive performance are unrelated to vitamin D effects on Ca and P absorption (Lauridsen, 2014).

To become biologically active, vitamin D_3 must undergo hydroxylation at the 25 position and at the one position, which takes place in the liver and the kidney, respectively. Because it is the double hydroxylated form, $1,25(OH)_2D_3$, that is needed to activate the vitamin D receptor in the small intestine, it has been speculated that providing animals with an vitamin D_3 analogs or metabolite, in which either the 1 or the 25 position has already been hydroxylated, will allow animals to better utilize vitamin D_3. Indeed, commercial forms of $1(OH)D_3$ and $25(OH)D_3$ are available and the reproductive performance of sows may be improved if sows are fed $25(OH)D_3$ rather than a similar amount of vitamin D_3 (Lauridsen et al., 2010; Zhou et al., 2017; Zhang and Piao, 2021). Developing gilts- fed diets containing $25(OH)D_3$ rather than vitamin D_3 had increased fibula ash and improved structural soundness, and in lactating sows, $25(OH)D_3$ resulted in improved Ca balance compared with feeding vitamin D_3. Inclusion of $25(OH)D_3$ instead of vitamin D_3 in diets for sows over multiple parities also resulted in increased plasma, colostrum, and milk concentrations of $25(OH)D_3$ (Weber et al., 2014). Likewise, in growing pigs, the inclusion of $25(OH)D_3$ in diets resulted in increased ATTD of protein and ash (Duffy et al., 2018). Thus, it appears that using $25(OH)D_3$ instead of vitamin D_3 in diets for sows and pigs may offer some benefits of which several seem to be associated with non-calcemic effects. Two reviews of the impacts of using $25(OH)D_3$ in diets for pigs have been published recently (Zhang and Piao, 2021; Lütke-Dörhoff et al., 2022). By summarizing data from a large number of experiments, it was demonstrated that plasma concentration of $25(OH)D_3$ is increased if $25(OH)D_3$ is added to the diet instead of vitamin D_3, which was assumed to be the result of a more efficient absorption of $25(OH)D_3$ than of vitamin D_3 (Lütke-Dörhoff et al., 2022). Improvements in circulating vitamin D levels of sows fed $25(OH)D_3$ were also reported in the review by Zhang and Piao (2021), which was proposed to result in increased sow reproductive performance and increased bone health of sows. Data from several experiments also demonstrated that the addition of $25(OH)D_3$ to sow diets resulted in increased fat and (or) protein concentration in milk, increased pig growth performance before and after weaning, and increased bone strength of pigs after weaning (Zhang and Piao, 2021).

Results of two recent experiments also indicated that using the $1(OH)D_3$ analog in diets for sows, in addition to levels of vitamin D_3 that were well above the requirement, resulted in increased digestibility of not only Ca and P but also of DM and gross energy (Lee and Stein, 2022; Lee et al., 2022). Because of the increased digestibility of gross energy, metabolizable energy in the diets with $1(OH)D_3$ was almost 100 kcal greater than in the control diets, which corresponds to around 485 kJ. Adding $25(OH)D_3$ to the diets resulted in a similar increase in energy digestibility as did the addition of $1(OH)D_3$ indicating that the two molecules are equally efficient in increasing the digestibility of Ca, P, energy, and DM (Lee et al., 2022). The mechanisms responsible for the increased digestibility of DM and energy are not understood and it is possible that if the concentration of an equivalent dose of vitamin D_3 had been used, results would have been similar, but because $25(OH)D_3$ and $1(OH)D_3$ were only offered on top of the normal dose of vitamin D_3, additional research is needed to address this hypothesis.

Digestibility and requirements of sodium and chloride

Sodium and Cl are the principal anions and cations in the body and are needed for osmotic pressure regulation and for regulation of acid-base balance. As a consequence, Na and Cl are the major determinants of the electrolyte balance of a diet (i.e., Na + K – Cl), and therefore, influence the net balance between anions and cations (Guzman-Pino et al., 2015). Both Na and Cl are provided in diets by common salt (NaCl) and in addition to dietary Na, additional Cl in the form of hydrochloric acid is added in the fundic region of the stomach to assist in the digestion of protein, whereas Na is added from bicarbonate secreted primarily from the pancreatic duct cells. As a consequence of the endogenous secretion of Na and Cl prior to the cecum, ileal digestibility of both minerals is usually negative, but due to absorption in the hindgut, the ATTD of Na is between 75 and 95% (Table 4). Although sodium is well digested in diets without phytase, the ATTD of Na is usually increased by addition of phytase to the diets (She et al., 2018a; Arredondo et al., 2019; Espinosa et al., 2021b; Lagos et al., 2022).

Requirements for Na and Cl by growing, finishing, and reproducing swine are believed to be met if 0.40% NaCl is added to diets for all groups of pigs (NRC, 2012) and because of the low cost of salt, it is common practice to add 0.40% NaCl to swine diets. However, requirement estimates of only 0.11% Na and 0.11% Cl for pigs from 25 kg to market have also been proposed (Centraal Veevoederbureau, 2020).

Results of recent research have demonstrated that weanling pigs have a requirement for NaCl that is considerably greater than in older pigs if measured as a percentage of the diet (NRC, 2012). Indeed, inclusion of up to 0.60% NaCl in diets for weanling pigs that contained approximately 0.20% Na before salt addition increased growth performance of pigs (Mahan et al., 1996; 1999). More recently, inclusion of 0.78% NaCl in diets for weanling pigs improved growth performance compared with pigs fed a diet with 0.35% NaCl, and requirements for 7–12 kg pigs of 0.38% Na and 0.38% Cl were estimated (Shawk et al., 2019). These estimates correspond with current requirements of 0.40, 0.35, and 0.28% Na and 0.50, 0.45, and 0.32% Cl in diets for pigs from 5 to 7 kg, 7–11 kg, and 11–25 kg, respectively (NRC, 2012).

Digestibility and requirements of potassium

Potassium is the third most abundant mineral in the body and as the major extracellular cation, K is involved in acid-base regulation in the body as well as maintenance of osmotic pressure via the K-Na pump. Like Na, K is easily digested and absorbed and ATTD is greater than 80% (Table 4). Because K may chelate to phytate, there is usually a small, but consistent, increase in ATTD of K (2–8% units) if microbial phytase is added to the diet, and the response to increased dosages of phytase is usually quadratic with the maximum response obtained at a level of 1 000–2 000 phytase units per kg of diet (She et al., 2018a; Arredondo et al., 2019; Espinosa et al., 2021b; 2022; Lagos et al., 2022). The requirement for K is 0.30% in diets for weanling pigs, but this requirement is reduced to 0.20–0.30% in finishing pigs and sows (NRC, 2012; Centraal Veevoederbureau, 2020). In practical diets for pigs, the natural ingredients usually provide sufficient K to meet the requirement, and K is, therefore, not supplied from mineral ingredients in the diets.

Table 4
Apparent total tract digestibility of minerals by growing pigs fed corn-soybean meal based diets.

Mineral	n	Apparent total tract digestibility, %			Phytase effect[1]
		Average	Minimum	Maximum	
Na[2]	5	76	54	88	Yes
Mg[3]	5	25	11	46	Yes
K[4]	5	82	77	87	Yes
S[5]	2	82	79	85	No
Cu[6]	4	27	9	37	Yes
Zn[7]	2	39	32	45	Yes
Fe[8]	3	25	20	30	Yes
Mn[9]	3	28	19	34	No

[1] Indicates if the apparent total tract digestibility is increased by addition of microbial phytase to the diet.
[2,3,4] Data from She et al. (2018a): Arredondo et al. (2019): Espinosa et al. (2021b; 2022): and Lagos et al. (2022).
[5,7] Data from She et al. (2018a) and Arredondo et al. (2019).
[6] Data from Liu et al. (2014): She et al. (2018a): Arredondo et al. (2019): and Espinosa et al. (2022).
[8,9] Data from Liu et al. (2014): She et al. (2018a): and Arredondo et al. (2019).

Digestibility and requirements of magnesium

Magnesium is a bone mineral that has many additional physiological functions as well as being a co-factor in numerous enzyme systems in metabolism (McDowell, 2003a). Because Mg is a cation, it can chelate with phytate and the ATTD of Mg, therefore, usually is only between 20 and 40% in corn-soybean meal-based diets without microbial phytase (Table 4; She et al., 2018a; Arredondo et al., 2019; Espinosa et al., 2021b; 2022). However, if microbial phytase is added to the diets, ATTD of Mg may increase to almost 80% because of the release of Mg from phytate (She et al., 2018a, Arredondo et al., 2019; Espinosa et al., 2021b; 2022). There are also indications that the ATTD of Mg increases as pig weight increases from around 25 to around 100 kg (Lagos et al., 2022). Due to antagonism by Mg on P absorption, Mg may negatively influence absorption of P from the intestinal tract and the ATTD of P in magnesium phosphate is less than in monocalcium phosphate or monosodium phosphate (Lopez et al., 2022).

It is believed that there is sufficient Mg in commercial diets for pigs to meet the requirement for Mg because soybean meal contains Mg and limestone and feed phosphates are often contaminated with Mg in the form of magnesium oxide or magnesium phosphate (Lee et al., 2023b). Corn-soybean meal diets, therefore, usually contain 0.12–0.15% Mg (She et al., 2018a; Arredondo et al., 2019), which is well above the requirement for growing and reproducing swine that is estimated at 0.04 and 0.06%, respectively (NRC, 2012). As a consequence, Mg is usually not included in the mineral premixes added to diets for pigs fed practical diets (Lee and Stein, 2023). However, based on factorial calculations of Mg deposition in tissue and in milk, it has been concluded that current requirement estimates may be marginal (Tybirk, 2021). It is, therefore, possible that in low protein diets with low levels of soybean meal, the natural provision of Mg does not meet the requirement of weanling pigs, and diets for lactating sows without phytase may also become marginal in Mg (Tybirk, 2021). There are, however, no data from recent requirement studies that have addressed this hypothesis and research in this area is warranted.

Digestibility and requirements of sulfur

Sulfur is an essential nutrient in diets for pigs and other monogastric animals and is needed for the synthesis of chondroitin, taurine, glutathione, and other S-containing compounds in the body. However, S is also included in the S-containing amino acids in the diet (i.e., cysteine and methionine) and it is, therefore, difficult to separate the needs for S from the needs for the S-containing amino acids. Indeed, if animals are fed an S-free diet, they will use cysteine or methionine to furnish the sulfur needed in other body components and the requirement for the S-containing amino acids may, therefore, increase (McDowell, 2003b). The ATTD of S is usually greater than 75%, but digestibility is not increased by addition of microbial phytase to the diets because S does not chelate with phytate (Merriman et al., 2016; She et al., 2018a; Arredondo et al., 2019).

Corn-soybean meal-based diets usually contain 0.20–0.25% S, which is believed to be more than enough to meet the requirement of both weanling, growing, and reproducing swine. The bigger concern is often that there may be too much S in the diets due to inclusion of corn co-products that may be high in S (Kerr et al., 2011; NRC, 2012). However, feeding diets based on corn, soybean meal, and distillers dried grains with solubles that contained 0.38% S did not change feed preference or growth performance of growing pigs compared with pigs fed a control diet that contained 0.19% S (Kim et al., 2012b). It is likely that the reason dietary S had no negative effect is that excess absorbed S is mostly excreted in the urine and not accumulated in body tissues (Kim et al., 2014). In contrast, feeding diets that contained up to 1.20% S linearly reduced growth performance of weanling pigs (Kerr et al., 2011). It therefore appears that diet S-concentration needs to be greater than 0.38% before negative effects are observed.

Digestibility and requirements of copper

Copper is a micromineral that is needed in many reactions in the body including pigmentation, development of connective tissue, cellular respiration, and synthesis of hemoglobin. Copper is also a component of metalloenzymes and plays a role in oxidation–reduction reactions in the body and in regulating oxidative stress (Byrne and Murphy, 2022).

Corn contains less than 5 mg/kg of Cu and soybean meal contains 12–25 mg/kg (NRC, 2012; Espinosa et al., 2021b; 2022) and in a corn-soybean meal diet without supplemental Cu, the concentration of Cu is less than 5 mg/kg (Liu et al., 2014). The ATTD of Cu in a corn-soybean meal diet fortified with Cu sulfate is approximately 27% (Table 4), but because Cu may chelate to phytate, the digestibility of Cu is increased by addition of microbial phytase to the diets (She et al., 2018a; Arredondo et al., 2019; Espinosa et al., 2022).

Inclusion of Cu in diets for pigs is often accomplished by using copper sulfate, which is an inexpensive source of Cu. The requirement for Cu for all groups of pigs is less than 20 mg/kg diet (NRC, 2012), but inclusion of up to 200 mg/kg positively impacts growth performance of growing pigs (Espinosa et al., 2017; Villagómez-Estrada et al., 2020a), and it is, therefore, common practice in many countries to include between 100 and 160 mg/kg of Cu in diets for weanling and growing-finishing pigs. Indeed, commercial diets for weanling pigs in the U.S. on average contain between 150 and 160 mg/kg Cu and diets for growing-finishing pigs contain between 50 and 80 mg/kg Cu, whereas diets for sows and developing gilts only contain 15–20 mg/kg Cu (Flohr et al., 2016). In commercial diets in Brazil, diets for weanling pigs contain 120–140 mg/kg Cu and diets for growing-finishing pigs contain 80–100 mg/kg, whereas diets for sows and developing gilts in Brazil contain 50–100 mg Cu/kg (Dalto and da Silva, 2020). However, in commercial diets in China, the concentration of Cu in weanling pig diets is 75–80 mg/kg whereas diets for growing-finishing pigs, developing gilts, and sows contain 18–20 mg/kg Cu (Yang et al., 2021).

One of the reasons for the greater growth performance of pigs fed diets with elevated levels of Cu is that feed intake is increased because pigs have a greater preference for eating diets with increased concentrations of Cu compared with diets with less Cu (Villagómez-Estrada et al., 2020b). Pigs fed diets with greater levels of Cu also have reduced microbial protein in the hindgut (Espinosa et al., 2019a), which may be a result of the bacteriostatic properties of Cu. Pigs with reduced microbial activity in the hindgut can utilize more of the dietary energy for growth and have reduced endogenous losses of fat from the digestive tract (Espinosa et al., 2021a). It is also possible that high levels of Cu positively impact genes involved in postabsorptive lipid metabolism (Espinosa et al., 2020), and weanling pigs are better able to maintain growth performance during heat stress if 150 mg/kg of Cu from copper hydroxychloride is included in the diets rather than 20 mg/kg (Espinosa et al., 2019b).

Although copper sulfate is the source of Cu that historically has been used in diets for pigs, there are indications that dicopper oxide may result in improved growth performance of pigs compared with copper sulfate (Blavi et al., 2021). Dicopper oxide also induces less systemic oxidation and inflammation than copper sulfate (Forouzandeh et al., 2022). Although elevated levels of dietary Cu may result in changes in intestinal microbiota, there is no evidence that this results in selection of microbes that are resistant to antibiotics (Villagómez-Estrada et al., 2020a; Brinck et al., 2023).

If given a choice, pigs show a preference for eating diets containing Cu hydroxy chloride instead of diets containing copper sulfate (van Kujik et al., 2019a), and copper hydroxy chloride reduces oxidative stress in pigs to a greater extent than copper sulfate (Huang et al., 2015). Microbial phytase is also more stable in a premix containing Cu hydroxy chloride rather than Cu sulfate (Lu et al., 2013). Use of chelated Cu methionine hydroxy analog rather than copper sulfate results in improved growth performance of pigs (Ma et al., 2015; Gonzalez-Esquerra et al., 2019; Ren et al., 2020), and the use of a chelated Cu methionine hydroxy analog results in increased digestibility of P (Ren et al., 2021). It therefore appears that chelated Cu or Cu hydroxy chloride offers benefits over the use of Cu sulfate and these sources are, therefore, often used in diets for pigs. Additional details of copper metabolism and impacts of dietary copper on pig growth performance and health were recently reviewed (Espinosa and Stein, 2021).

Digestibility and requirements of zinc

Zinc is primarily used in the body as a co-factor for reactions involving proteins and metallo enzymes. Corn and soybean meal contain around 15 and 45 mg/kg Zn, respectively (Arredondo et al., 2019; Espinosa et al., 2021b; 2022), and a corn-soybean meal diet without supplemental Zn, therefore, contains around 20 mg/kg Zn (Liu et al., 2014). The most common sources of Zn in diets for pigs are zinc oxide and zinc sulfate and the ATTD of Zn in a corn-soybean meal diet fortified with around 100 mg/kg of Zn from zinc sulfate and no microbial phytase is around 39% (Table 4). However, the digestibility of Zn may be greater if a chelated Zn methionine-hydroxy analog is used rather than Zn sulfate (Liu et al., 2014). The digestibility of Zn also increases if microbial phytase is added to the diet (Arredonde et al., 2019) because native Zn easily binds to phytate (Schlegel et al., 2013) and 500 phytase units may be equivalent to 27 mg/kg of Zn (Bikker et al., 2012).

The requirement for Zn is estimated at 100 mg/kg in diets for weanling pigs and sows, but only 50 mg/kg in growing and finishing pigs (NRC, 2012). However, inclusion of 2 000–3 000 mg/kg Zn in diets for weanling pigs results in increased growth performance (Buff et al., 2005; Hollis et al., 2005; Feldpausch et al., 2018), and elevated levels of Zn also modulates intestinal microbiota (Pérez et al., 2011). However, feeding 3 000 mg/kg of dietary Zn from Zn oxide for 5 weeks postweaning elevates Zn concentration in serum, liver, and kidney, and reduces Cu in serum and liver in comparison with pigs fed 100 or 1 000 mg Zn per kg (Dalto et al., 2023). Nevertheless, because of the increased growth performance of weaned pigs fed diets with elevated levels of Zn, inclusion of between 2 000 and 3 000 mg/kg of Zn in diets for weanling pigs is commonly practiced in many countries. Indeed, a recent survey of commercial swine diets in the U.S. demonstrated that phase 1 and phase 2 diets for weanling pigs on average contain 3 000 and 2 000 mg/kg of Zn, respectively, whereas diets for growing and finishing pigs on average contain 75–100 mg/kg and sow diets contain around 125 mg/kg (Flohr et al., 2016). Likewise, in Brazil, commercial phase 1, 2, and 3 diets contain around 2 000, 1 000 and 500 mg/kg of Zn, respectively, whereas growing and finishing diets contain only around 100 mg/kg Zn (Dalto and da Silva, 2020). In contrast, commercial diets in China contain Zn at levels close to NRC requirements (Yang et al., 2021) and the European Union recently banned the use of elevated levels of Zn in diets for weanling pigs.

Recent data indicate that there are no benefits on pig growth performance or carcass characteristics of providing more than 50 mg/kg of zinc to finishing pigs (Cemin et al., 2019b). However, due to antagonisms between Zn and other minerals, inclusion of high levels of Zn in diets results in reduced digestibility of Ca and P (Blavi et al., 2017). To avoid this reduction and to reduce fecal excretion of Zn, inclusion of lower levels of Zn from Zn chelates is sometimes practiced, but inclusion of 500 mg/kg of Zn from Zn amino acid or polysaccharide chelates did not result in the same growth performance as 2,000 mg/kg of Zn from zinc oxide (Hollis et al., 2005). If the same level of Zn from a chelated Zn methionine-hydroxy analog as of Zn from Zn oxide was used, no difference in growth performance was observed, but the ATTD of Ca and P was improved (Ren et al., 2020). Inclusion of a zinc-polysaccharide chelate in diets for sows increased digestibility of Zn in lactation if the zinc polysaccharide was added to a corn-soybean meal diet, whereas digestibility was reduced if the diet contained corn distillers dried grains with solubles (Holen et al., 2020). For weanling pigs, the use of a glycine-chelated source of Zn instead of Zn sulfate did not change growth performance during the initial 3 weeks postweaning, but pigs fed the chelated source of Zn had greater solubility of Zn in the stomach and small intestine and increased metacarpal concentration of Zn compared with pigs fed the diet with Zn sulfate (Schlegel et al., 2010). Likewise, if zinc hydroxychloride is used in diets for growing-finishing pigs instead of zinc sulfate, carcass characteristics may be improved (Cemin et al., 2019a). Results of a recent meta-analysis also indicated that Zn from zinc hydroxychloride fed to weanling or growing pigs tends to increase the gain to feed ratio from weaning to market, and in the finishing phase, average daily gain, the gain-to-feed ratio, and the average lean percentage are increased if zinc hydroxychloride rather than other forms of Zn is used (van Kujik et al., 2019b). A reduced expression of pro-inflammatory genes in the intestines was also observed in finishing pigs fed an amino acid-chelated source of Zn rather than ZnCl although serum concentrations of Zn were not different between pigs fed the two sources of Zn (Medida et al., 2023). It is, therefore, possible that there are certain benefits to using chelated or hydroxylated forms of Zn rather than Zn oxide or Zn sulfate.

Digestibility and requirements of iron

Iron is needed in the body as part of many enzymes and as a crucial part of hemoglobin, myoglobin, and transferrin. Iron is deficient in sow milk and because pigs are born with low Fe stores, pigs kept in confinement without access to soil need supplemental Fe, usually in the form of an Fe injection, within a few days of life to maintain plasma hemoglobin and hematocrit levels (Peters and Mahan, 2008; Williams et al., 2020a). Recent data indicate that a single injection with Fe within the first 7 days of life is sufficient for pigs to maintain optimum Fe status (Williams et al., 2021). After weaning, pigs will obtain Fe from their diets that are usually fortified with iron sulfate or another source of Fe. The concentration of Fe in corn and soybean meal is around 15 and 80–100 mg/kg, respectively (NRC, 2012; Arredondo et al., 2019; Espinosa et al., 2021b; 2022), but due to contamination with iron from other mineral sources, a corn-soybean meal diet without supplementation with Fe may contain up to 100 mg/kg of Fe (Liu et al., 2014).

The ATTD of Fe in a corn-soybean meal diet fortified with iron sulfate is around 25% (Table 4), but digestibility can be increased by inclusion of microbial phytase in the diet (She et al., 2018a; Arredondo et al., 2019). Likewise, Fe from an iron-amino acid chelate has a greater digestibility than iron from iron sulfate (Liu et al., 2014). Recently, it was concluded that Fe from iron carbonate is equally efficient at maintaining Fe status of pigs as iron sulfate indicating that the digestibility of Fe in iron carbonate is not different from that in iron sulfate (Williams et al., 2020b).

Requirements for Fe by weanling pigs is estimated at 100 mg/kg and the requirement is reduced to 60 mg/kg in growing pigs and 40 mg/kg in finishing pigs, whereas gestating and lactating sows have a requirement of 100 mg/kg (NRC, 2012). Increasing Fe in the diets above the requirement may antagonize absorption of Cu and Mn (Hansen et al., 2009). Commercial diets produced in the U.S. or Brazil for all groups of pigs contain Fe that is close to the NRC requirement (Flohr et al., 2016; Dalto and da Silva, 2020), whereas diets for all groups of pigs in China contain between 220 and 250 mg/kg Fe (Yang et al., 2021).

Digestibility and requirements of manganese

Manganese is needed in the body as a component of many enzyme systems and as part of superoxide dismutase (NRC, 2012). Manganese is also needed for development of the bone matrix and of cartilage (Byrne and Murphy, 2022).

Corn and soybean meal contain approximately 4 and 30 mg Mn per kg, respectively (Arredondo et al., 2019; Espinosa et al., 2021b; 2022), and a corn-soybean meal grower diet without supplemental Mn, therefore, contains around 12 mg Mn per kg (Liu et al., 2014). The ATTD of Mn in a diet containing corn, soybean meal, and manganese sulfate is 28% (Table 4), and there does not appear to be any impact of microbial phytase on Mn digestibility (She et al., 2018a; Arredondo et al., 2019). However, the ATTD of Mn from a Mn-amino acid chelate is greater than the digestibility of Mn from manganese sulfate (Liu et al., 2014).

The requirement of Mn by weanling pigs is believed to be 4 mg/kg, but the requirement may gradually decrease to 2 mg/kg in finishing pigs, whereas sows need 25 mg/kg (NRC, 2012). Most commercial diets for weanling and growing pigs in the U.S. contain between 18 and 35 mg/kg of supplemental Mn and sow diets are fortified with around 35 mg/kg (Flohr et al., 2016). However, commercial diets in Brazil and China are fortified with almost twice as much Mn as U.S. diets (Dalto and da Silva, 2020; Yang et al., 2021) although there does not seem to be any benefits of adding more than 8 mg/kg Mn to diets for growing-finishing pigs (Apple et al., 2004; Pallauf et al., 2012; Kerkaert et al., 2021). However, there may be some benefits on growth performance of using Mn hydroxychloride rather than Mn sulfate especially if diet Cu concentrations are elevated (Kerkaert et al., 2021). Cooking loss of pork chops from pigs fed a Mn-amino acid chelate was less than that of pigs fed Mn sulfate (Apple et al., 2004). Likewise, postpubertal gilts fed a Mn amino acid chelate had greater superoxide dismutase in corpora lutea than gilts fed a diet containing Mn sulfate (Studer et al., 2021). Superoxide dismutase activity in kidney, heart, and muscle of weanling pigs increased with increasing dietary Mn up to 16 mg/kg with no further increase after that (Pallauf et al., 2012). Overall, results of recent research with Mn indicate that there is little evidence that weanling and growing pigs fed corn-soybean meal diets need supplemental Mn above 8 mg/kg, but current requirement estimates (NRC, 2012) may not be sufficient to maximize growth performance. There may also be some benefits to using hydroxylated or amino acid-chelated Mn instead of Mn sulfate.

Conclusions

Digestibility of Ca and P in feed ingredients is most correctly determined as the STTD values because these values are additive in mixed diets. The impact of microbial phytase on digestibility of Ca and P needs to be taken into account in diet formulation, which may require knowledge about the efficacy of the specific phytase being used because newer phytases appear to release more Ca and P from phytate than older phytases. Digestibility of Ca and P by gestating and lactating sows is much less than in growing pigs and values for the STTD of P determined in sows need to be generated. Because of the negative impacts of excessive dietary Ca on pig growth performance, it is critical that ingredients and diets for pigs are analyzed for Ca to confirm that Ca is not provided in excess of the requirement. There is no evidence that vitamin D for growing and finishing pigs needs to exceed current requirement estimates, but it is possible sows will benefit from inclusions that are greater than current requirements. It is also possible that the 1(OH)D_3 analog and the 25(OH)D_3 metabolite may be beneficial in diets for sows and growing-finishing pigs, but more research is needed to elucidate the effects of these compounds. Current recommendations that all diets for pigs need to contain 0.40% salt to provide sufficient Na and Cl appear to be accurate for growing, finishing, and reproducing swine, whereas weanling pigs may need greater amounts. There is no need for inclusion of K in excess of what is provided by the raw materials in the diets. In contrast, it is possible that current recommendations for Mg in diets for weanling pigs and lactating sows are marginal and need to be increased, but inclusion of phytase in diets will increase digestibility of Mg. Inclusion of up to approximately 0.40% S in diets for weanling or growing pigs has no negative effects on diet palatability or pig growth performance, but if S inclusion increases to above 0.60%, feed intake may be reduced.

Current requirements for Cu, Zn, and Fe are likely sufficient to meet requirements of weanling, growing, and finishing pigs, but there are indications that pigs need more Mn than current requirements, although not all experiments have demonstrated a greater need for Mn. Unlike Cu, Zn, and Fe, the digestibility of Mn does not increase if microbial phytase is added to the diet, making it more critical that diets are fortified with the correct amounts of Mn. There is strong evidence that amino acid or protein-chelated microminerals or minerals with other chemical forms than sulfates or oxides have greater digestibility than microminerals in sulfate or oxide forms, and it is, therefore, likely that mineral inclusion rates can be reduced if these forms are used.

Ethics approval

Not applicable.

Data availability statement

Data or models were not deposited in an official repository. No new datasets were created.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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H.H. Stein: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Conceptualization.

Declaration of interest

None.

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