Modeling digestibility of dietary phosphorus in growing and finish pigs1

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ABSTRACT: Low P digestibility combined with intensive pig production can lead to water pollution. The aim of this paper was to develop a model able to represent P digestion in pigs across diets and contribute towards the reduction of P excretion. Phosphorus in plant feedstuffs includes some nonphytate P (NPP) that is readily digested but is mostly as organic phytate P (oP) that is indigestible unless it is dephosphorylated. The ability of pigs to dephosphorylate oP using endogenous phytase enzymes is limited and is a function of Ca intake. The effect of Ca (g/kg diet) on the proportion of oP dephosphorylated (kg/kg) in the small intestine (SI) and large intestine (LI) was determined as 0.26 – (0.015 × dietary Ca) and 0.69 – (0.059 × dietary Ca), respectively. The dephosphorylated oP in the LI was assumed to be indigestible and was excreted. Proportion of oP dephosphorylation (kg/kg) by microbial and plant phytase activity (FTU) in the stomach was estimated to be $0.56 \times [1 – \exp(–0.001 \times \text{FTU})]$ and $0.38 \times [1 – \exp(–0.002 \times \text{FTU})]$, respectively. Phosphorus digestibility (kg/kg) of NPP and dephosphorylated oP in the SI was assumed to be constant at 0.8. The model was used to predict P digestibility in 2 experiments by Stein et al. (2011) and Poulsen et al. (2010) and compare the predictions with experimental outcomes. The model successfully predicted the P digestibility to a range of dietary Ca concentrations and for 2 levels of supplementation with microbial phytase. However, the predictions overestimated P digestion systematically but always within a 10% margin of the observed values. The model could be a useful tool for formulating strategies to improve the efficiency of P digestion and reduce soluble P excretion in pigs.

Key words: dephosphorylation, modeling, phosphorus, phytase, phytate, pig

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INTRODUCTION

Phosphorus is an important mineral for metabolism and skeletal development of the pig. The majority of plant P is in the form of organic phytate P (oP). The oP molecule cannot be digested unless it is dephosphorylated by endogenous or exogenous phytase. Phytate dephosphorylation is mainly affected by pH within the lumen of the gastrointestinal tract and dietary Ca concentration. The low digestibility of P also contributes to high P excretion that may cause water pollution in the form of eutrophication. This paper describes the development of a mechanistic model to predict digestible P intake from 2 feed compositions and compare these predictions to actual values. The 2 sets of diets used for validation were based on corn (Zea mays) and soybean (Glycine max) meal (Stein et al., 2011) or on wheat (Triticum aestivum), barley (Hordeum vulgare), and soybean meal (Poulsen et al., 2010).

MATERIAL AND METHODS

The developed digestible P model is deterministic. In the stomach, dietary plant and microbial phytase dephosphorylate oP into nonphytate P (NPP). Plant and microbial phytase are inactivated in the small intestine (SI) due to the alkaline environment and because protease enzymes denature phytases. The pH of the stomach was assumed to be constant at 4.1 to avoid diurnal variation in digestibility. The dephosphorylation of oP by microbial and plant phytase in the stomach were assumed to be additive.

Data from Kies et al. (2006) who used graded levels of up to 15,000 phytase activity (FTU) microbial phytase/kg were used to derive an exponential equation for oP dephosphorylation by microbial phytase of Aspergillus niger. However, these authors examined effects of

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microbial phytase on overall P digestibility rather than on oP dephosphorylation. Expressing the effect of microbial phytase activity solely in terms of total P digestion fails to consider potentially negative effects of dietary Ca. Therefore, we assumed that digestibility of NPP from the lumen of the SI into the bloodstream was 0.80 (Sauvant et al., 2004) and back calculated the oP dephosphorylated in the stomach to derive Eq. [1]:

Phytate dephosphorylated (kg/kg) = 0.56 
= (1 – exp (–0.00104 × FTU)),

in which 0.56 is the maximum proportion of oP dephosphorylation, FTU is the microbial phytase activity, defined as the amount of enzyme that liberates 1 μmol of inorganic P in 1 min from 5.1 mmol solution of sodium oP at 37°C at pH 5.5, and residual SD (RSD) was 0.79.

Sauvant et al. (2004) analyzed phytase activity of various plant ingredients. For some of these, the oP dephosphorylation caused by plant phytase was estimated (Sauvant et al., 2004) and Eq. [2] was derived:

Phytate dephosphorylated by plant phytase (kg/kg) = 0.38 × (1 – exp (–0.00217 × FTU)),

in which 0.38 is the maximum proportion of oP dephosphorylation, FTU is plant phytase activity of the diet, and RSD = 0.24.

Data from Plumstead et al. (2008) who used ileal-cannulated pigs to quantify dephosphorylation of oP by endogenous SI phytase in response to dietary Ca. Calcium makes oP insoluble and indigestible by forming a Ca–oP complex. This relationship is expressed in Eq. [3]:

Phytate dephosphorylated by SI phytase (kg/kg) = 0.26 – (0.0158 × (Ca g/kg diet)),

in which SI is small intestine and RSD = 0.50.

In the large intestine (LI), dephosphorylation of remaining intact oP occurs by phytase of the microflora. However, absorption of NPP in the LI is negligible and it is excreted as soluble and environmentally hazardous P. Calcium also forms complexes with oP in the LI and these are excreted as insoluble P. Phytate dephosphorylation is linearly expressed as a function of Ca, using data of Sandberg et al. (1992) from ileal-cannulated pigs in Eq. [4]:

Phytate dephosphorylated by LI phytase (kg/kg) = 0.70 – (0.0593 × Ca g/kg diet),

in which LI is large intestine and RSD = 0.88.

The effect of various diet compositions onto P digestibility was studied by comparing corn–soybean meal-based diets used by Stein et al. (2011) and wheat–barley–soybean meal-based diets used by Poulsen et al. (2010). Both studies investigated the effect of P digestibility with graded dietary Ca content; Poulsen et al. (2010) also used 2 levels of supplementation with microbial phytase.

RESULTS AND DISCUSSION

The observed P digestibilities for Stein et al. (2011) diets were higher than those for the Poulsen et al. (2010) diets (Table 1). The difference was not surprising because Poulsen et al. (2010) did not use inorganic P whereas 45% of dietary P originated from easily digestible NaH₂PO₄ in Stein et al. (2011). If inorganic P supplementation is not taken into account, Poulsen et al. (2010) estimated higher P digestibility, mainly due to the wheat included in their diets. Wheat contains much more NPP than corn and more plant phytase to dephosphorylate oP, thus increasing P digestibility.

Predictions of P digestibility were within the 10% margin of that observed (Table 1), although the overestimation appeared systematic. A possible reason for the overestimation of P digestion for Stein et al. (2011) could be that the calculated total P content of the diet was 4.2 vs. 4.5 g/kg diet as analyzed. The total P content of Stein et al. (2011) diets needed to be reestimated because an estimate of the oP content of the diets was not provided.

The model reproduced the observed decrease in P retention with increasing dietary Ca. Even though the model predictions follow the same trend and as observed values, the slope of decrease in P digested at increasing dietary Ca is gentler. The difference could be explained by the assumed constant pH in the stomach. Calcium has a high acid-binding capacity and in diets with extreme Ca concentrations the pH of the stomach becomes more alkaline causing oP to be less soluble and forming Ca–oP complexes.

The predictions of consequences of addition of exogenous microbial phytase in the study of Poulsen et al. (2010) are good (Table 1). Differences between observed and predicted values were small, providing reassurance that the model is able to account for effects of phytase on P digestion. However, the model will have to be tested further on diets that include a wider level of microbial phytase inclusion.

The model reproduced satisfactorily the observed decrease in P digestion with increasing dietary Ca for both studies (Poulsen et al., 2010; Stein et al., 2011). In addition, the model accurately predicted consequences of the addition of 2 levels of microbial phytase on P digestion. The study of Poulsen et al. (2010) concluded that microbial and plant phytase act in an additive manner in the stomach. The slight but systematic overestimation of P digestibility by the model is the subject of current investigation. Mechanistic models provide an improved
understanding of P digestion and may enable formulation of pig diets that reduce environmental P pollution without compromising animal performance and maximize economic benefits of not supplementing with expensive inorganic P.

**LITERATURE CITED**


**Table 1.** Observed and predicted P digestibility of corn and soybean meal-based diets and wheat–barley–soybean meal-based diets used in experiments of Poulsen et al. (2010) and Stein et al. (2011), respectively. The root mean square error was 9 and 12% for P digestibility for Poulsen et al. (2010) and Stein et al. (2011), respectively.

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<th>Poulsen et al. (2010)</th>
<th>Stein et al. (2011)</th>
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<tr>
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<td>Diet 1</td>
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<td>P intake, g/d</td>
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<td>Predicted</td>
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¹FTU = phytase activity.

²750 FTU/kg *Aspergillus niger* added.