COMPOSITION AND DIGESTIBILITY OF DIFFERENT SOURCES OF FEED PHOSPHATES BY GROWING PIGS

BY

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THESIS

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ABSTRACT

Three experiments were conducted to determine the composition and digestibility of different sources of feed phosphates. In Exp 1, the hypothesis was that the process of production of feed phosphates removes most impurities including those potentially harmful for growing pigs. Seven sources of monocalcium phosphate (**MCP**), 4 of dicalcium phosphate (**DCP**), 2 of monosodium phosphate (**MSP**), and 1 magnesium phosphate (**MgP**) were used. Each feed phosphate was analyzed for minerals and then the P and Ca bound to impurities was calculated. Results indicated that the concentration of macro minerals were not different within each source of feed phosphate; whereas, micro minerals were more variable. For the potentially harmful minerals, the feed phosphates had variable concentrations but lower than the level of tolerance of the animal for all feed phosphates. In conclusion, the process to produce feed phosphates appears to be effective in generating a product with a specified concentration of P and low concentrations of potentially harmful minerals. In Exp. 2, the hypothesis was that P in feed phosphates from volcanic (igneous) sources have a greater digestibility than feed phosphates from sedimentary deposits when fed to growing pigs. A source of MCP and MSP from volcanic deposits and from non-volcanic (sedimentary) deposits were procured. Four diets were formulated to contain each source of phosphate as the sole source of P. A P-free diet was also formulated to estimate the endogenous P loss from pigs. Forty pigs were allotted to the 5 diets and housed individually in metabolism crates. Collection of feces took place 4 d after a period of adaptation of 5 d. Results indicate that the apparent total tract digestibility (**ATTD**) and standardized total tract digestibility (**STTD**) of P were not different between MCP and MSP from volcanic deposits and MCP and MSP from non-volcanic deposits. Values of digestibility were in agreement with previous data for STTD of P in MCP and MSP. In conclusion, the hypothesis was rejected because no

differences were found between the volcanic and non-volcanic feed phosphates. In Exp. 3, the hypothesis was that the ATTD and STTD of P in feed phosphates was increased by the use of microbial phytase when fed to growing pigs. A source of MCP, one source of MSP, and one source of MgP were procured. Three corn-soybean based diets were formulated to included 0, 500, or 4,000 units of microbial phytase (**FTU**) per kg but with no inclusion of feed phosphates. Nine additional diets were formulated by adding each of the 3 feed phosphates to the 3 basal diets. A P-free diet was formulated to estimate basal endogenous loss of P. A total of 13 diets were used in the experiment. One-hundred and seventeen pigs were allotted to the 13 diets for a total of 9 replicate pigs per diet. Each pig was housed individually in metabolism crates that allow the total collection of feces. A period of 5 d was given to the pigs for adaptation to the diet, prior to a 4 d collection period. Results indicated that the ATTD and STTD of P increased in all diets with the inclusion of phytase. However, the ATTD and STTD of P in the feed phosphates were not affected by the inclusion of phytase. This implies that the increase in the ATTD and STTD of P observed in the mixed diets was due to the release of P from phytate in corn and soybean meal but not from an increase in digestibility of P in feed phosphates. Results also indicated that MgP had a lower ($P < 0.05$) ATTD and STTD of P than MCP and MSP. In conclusion, the inclusion of microbial phytase did not increase the digestibility of P in feed phosphates.

Key words: digestibility, feed phosphates, impurities, phytase, pigs, volcanic

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CHAPTER 1: INTRODUCTION

The low availability of P in plant ingredients makes the supplementation with inorganic sources of P a necessity when diets for swine are being formulated (Jongbloed et al., 1991). The most used inorganic sources of P to meet the requirements of pigs are feed phosphates, such as monocalcium phosphate (**MCP**), dicalcium phosphate (**DCP**), and monosodium phosphate (**MSP**; Cromwell et al., 1993; Petersen et al., 2011). The process of production of feed phosphates start with the mining of the raw material called phosphate rock in the form of ore, which may have a volcanic or sedimentary origin (Leikam and Achorn, 2005). Rock phosphate is used to produce phosphoric rock via treatment with sulfuric acid. Phosphoric acid is then used to produce the feed phosphates by reaction with another mineral to produce a phosphate salt. As an example, calcium carbonate is used to produce MCP and DCP (Baker, 1989; Freitas and Giulietti, 1997; Gard, 2005).

The ores of rock phosphate from sedimentary sources are constituted mainly by francolites, which is a variety of mineral that contains phosphate (PO_4) and carbonate (CO_3) among other elements. The presence of carbonate in francolites will determine the grade of P that the phosphoric acid can reach if it is produced from sedimentary ores (Stewart et al., 2005). In contrast, the ores of rock phosphate from igneous, also called volcanic, sources are constituted mainly by fluorapatite and hydroxyapatites, which contains mainly PO_4 and Ca. The concentrations of P in ores from volcanic and sedimentary ores can be similar if the grade of substitution of PO_4 for CO_3 in francolites is low (Stewart et al., 2005). Both the concentration of P in phosphate rock and the concentration of impurities may be a factor that can affect the final concentration of P on feed phosphates, and since sedimentary sources contain more impurities

and may have a lower concentration of P compared with volcanic sources, feed phosphates from volcanic sources may have a greater concentration of P (Lindgren, 1913; Leikam and Achorn, 2005).

The degree to which a nutrient disappears after passing through the gastrointestinal tract of the animal is defined as digestibility (Stein et al., 2007), which may be expressed in several ways. In the case of P, because there is no significant absorption of P in the hindgut, apparent total tract digestibility (**ATTD**) is often determined (Bohlke et al., 2005; NRC, 2012). However, a correction for the endogenous P loss is necessary to obtain values that are additive in mixed diets. Correction of ATTD values with endogenous P loss allows for the calculation of the standardized total tract digestibility (**STTD**) of P (Stein et al., 2007). Unlike P in plant ingredients, the P in feed phosphates is not bound to phytic acid, which results in a high ATTD and STTD of P (Kiarie and Nyachoti, 2010; NRC, 2012; Baker et al., 2013; González-Vega et al., 2015; Kwon and Kim, 2017; Lee et al., 2019). Results of recent research indicate that inclusion of phytase increases the digestibility of Ca in calcium carbonate (González-Vega et al., 2015b; Walk, 2016; Lee et al., 2019). However, the effect of phytase on the digestibility of P in feed phosphates has not been elucidated.

Because of the reduced contamination with other minerals in volcanic rock phosphate, it is possible that the digestibility of P in feed phosphates based on volcanic rock is increased compared with phosphates produced from non-volcanic sources. However, the hypothesis that feed phosphates from volcanic sources may have a greater digestibility than feed phosphates from sedimentary sources has not been experimentally confirmed.

Therefore, the objective of the work included in this thesis is to determine if the concentration of P and impurities are different between feed phosphates produced from volcanic

and sedimentary sources of rock phosphate, and if the ATTD and STTD of P is greater in feed phosphates of volcanic origin compared with sedimentary origin.

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CHAPTER 2: PHOSPHORUS AND SWINE NUTRITION: LITERATURE REVIEW

INTRODUCTION

There are 6 classes of nutrients that have to be supplied to any animal to support adequate growth, development and in the case of livestock, production. Minerals are required nutrients that are supplied in relative low concentrations in diets fed to pigs, and Ca and P are 2 of the 7 macro minerals that are required. These two minerals are required in greater amounts compared with other minerals. However, feed ingredients traditionally used in swine nutrition are low in Ca and often have a low digestibility of P. To provide sufficient quantities of digestible Ca and P, diets for pigs are usually supplemented with limestone and feed grade phosphates (Cromwell, 2005).

Phosphorus does not naturally occur in nature because it is highly reactive and unstable. Instead, P is present in more stable forms such as phosphates and ortophosphates (Veum, 2010). Feed grade phosphates may be produced by the wet process method, which consists of the reaction of one of those stable forms of P, mainly phosphate rock obtained from either sedimentary or volcanic (igneous) mines, with sulfuric acid, to remove undesirable elements that can be harmful for the animal. The product of this reaction is phosphoric acid, which is used to produce feed phosphates after reaction with other minerals such as Ca, Mg, Na, or ammonium, which results in production of monocalcium phosphate, dicalcium phosphate, tricalcium phosphate, magnesium phosphate, mono-di sodium phosphate, or ammonium phosphate (Birky, 2017). However, dicalcium phosphate and monocalcium phosphate are the most used sources of feed phosphates in swine diets.

REQUIREMENTS FOR PHOSPHORUS BY PIGS

Phosphorus is needed in many essential physiological functions, including development and maintenance of bone tissue. Phosphorus deficient diets fed to pigs results in lower growth performance and reduced bone strength (Cromwell et al., 1972). Requirements for P are affected by body weight, the use of ractopamine and feed allowance (NRC, 2012). In the case of gestating sows, parity, litter size and day of gestation are the factors that may affect the requirement of P (NRC, 2012). Requirements for P may be expressed based on the standardized total tract digestibility (**STTD**) of P, which is believed to result in the most accurate provision of P in diets (Almeida and Stein, 2010). The requirements for P for growing pigs from 5 to 135 kg, and for gestating and lactating sows and boars have been reported (Table 2.1).

Growing Pigs

Several studies have been conducted to estimate requirements of P in growing pigs (Aubel and Hughes, 1936; Ketaren et al., 1993; Ekpe et al., 2002). However, NRC (2012) provides requirement estimates for different weight classes of pigs and the different stages of production. The requirement for P for growing and finishing pigs change with age and weight of the animal. As the weight of the pig increases, the requirement expressed as percentage of the diet decreases. But if the requirement is expressed as grams per day, it will increase as pig body weight increases. The estimated requirements of P used in formulation of diets results in maximum growth and efficiency of feed utilization, which is desired in pork production, but it may not always result in maximum bone mineralization (Cromwell, 2005; NRC, 2012) because the requirement to maximize bone ash is greater than the requirement to maximize growth performance.

Traditionally, the requirement for P and Ca were expressed as total Ca or total P, but research during the last 2 decades led to the concept of STTD P, which results in more accurate diet formulation due to variation in the availability of P in different ingredients (Cromwell, 2005). However, to formulate diets based on STTD of P, the STTD of all feed ingredients as well as the STTD requirement of the pigs need to be known (NRC, 2012).

Peo (1991) suggested that adequate P nutrition for pigs in different stages of production will depend on 3 key factors; i.e., an adequate supply of P and Ca, an adequate Ca:P ratio, and the presence of an adequate amount of vitamin D. Several studies have been conducted to determine the adequate ratio of Ca:P to maximize growth and minimize excretion of these nutrients (Fan and Archbold, 2012; González-Vega et al., 2016a; 2016b; Lagos et al., 2019a; 2019b)

Gestating Sows

Gestating sows have a greater requirement for P and Ca than growing-finishing pigs if expressed on a percentage basis due to the lower feed intake in gestation sows. The need for P for fetal growth increases from early to late gestation which results in an increase in P-requirement of sows during this period (Cromwell, 2005). The values reported by NRC (2012) are based on a feeding level of 1.8 to 2.0 kg of feed per day, but if daily feed intake is less than 1.8 kg it is recommended to include greater levels of Ca and P to meet the requirement. In contrast, if feed intake is greater than 2.0 kg of feed per day, Ca and P in the diet may be reduced. Parity of the sows also affects the requirement and first-parity sows have a greater need for Ca and P for bone mineralization and skeletal development than older sows (NRC, 2012). Second and third-parity sows also have a greater requirement for Ca and P than older sows. However, the excretion of Ca and P in gestating and lactating sows remain stable compared with

non-gestating sows despite the increased intake (Giesemann et al., 1998). This indicates a higher retention and use of Ca and P during the period of fetal growth and milk production.

The requirement for P is not constant during pregnancy, especially for second parity or older sows (NRC, 2012). During the first 2 months of gestation, the requirement for P is primarily a result of the need to restore body reserves from the previous lactation. The mineralization of the fetus takes places mainly in the last month of pregnancy, which will increase the requirement for P during this time (Jongbloed et al., 1991).

Lactating Sows

To determine the requirement for P for milk production in lactating sows, it is necessary to know both the quantity of milk produced and the P concentration in the milk. However, the milk yield of a sow is difficult to measure. Values reported in the literature are often results of equations to obtain an approximate value (Noblet and Etienne, 1989; Jongbloed et al., 1991). An accurate estimation of the concentration of P in milk is also difficult to obtain. Jongbloed et al. (1991) reported values of 1.2 to 1.7 g of P per kg of milk, but Hughes and Hart (1935) reported values between 0.84 and 1.2 g/kg. Other studies have been conducted to estimate the nutritional value of sows milk, but with no values for P concentration (Klaver et al., 1981; Tilton et al., 1999; Aguinaga et al., 2011).

The current requirements by NRC (2012) are based on a growth model and takes into account the parity of the sow, the litter size, day of lactation, expected body weight after farrowing, and the expected mean daily weight gain of nursing pigs. These factors along with an estimate of the digestibility of the P in the milk can be used to estimate the requirement for P in

the sow to successfully support the growth of the litter with a minimum resorption of P from bones (Jongbloed et al., 1991).

FUNCTIONS OF PHOSPHORUS

Phosphorus is important for several functions in the body such as bone mineralization, energy metabolism, nucleic acid synthesis, and being part of cell membrane structures (Gropper et al., 2009).

Bone Mineralization

Approximately 85% of the P in the body is present in skeletal tissue as amorphous calcium phosphate or crystalline calcium phosphate such as hydroxyapatite. The ratio of Ca:P in the amorphous forms is approximately 1.3:1; whereas, the ratio in crystalline forms of P is 1.5 to 2.0:1 (Gropper et al., 2009).

Phosphorus that is not part of the bone, is present in blood, cellular fluids, and soft tissues (Gropper et al., 2009; Veum, 2010). Three hormones regulate how P is distributed in the body. Parathyroid hormone (**PTH**) and calcitriol (1,25 – dihydroxycholecalciferol) promote resorption of phosphate from bone to increase P in serum; whereas, calcitonin promotes uptake of P for bone mineralization (Veum, 2010). Together, these hormones ensure availability of P for the different functions in the body (Gropper et al., 2009). Creatine phosphate, also known as phosphocreatine, is a carrier and donor of energy in muscles (Bhagavan, 2002); whereas, uridine triphosphate (**UTP**) is a phosphate donor for intermediate substances in metabolism (Gropper et al., 2009).

Metabolic Functions

Both DNA and RNA contain P as part of their backbone (Gropper et al., 2009). Phosphorus is vital in the storage and transfer of energy in the form of phosphate bonds of high energy in molecules such as adenosine triphosphate (**ATP**), creatine phosphate, and UTP (Gropper et al., 2009).

In cell membranes, P is part of phospholipids, which are important for the cell membrane and its bilayer structure. Phospholipids have a polar region made of a phosphate group and a molecule of glycerol; whereas, the non-polar region consists of 2 fatty acids. Because of this particular composition, the cell wall can allow passage of certain substances making the membrane selectively permeable (Alberts et al., 2002; Gropper et al., 2009).

Deficiency of Phosphorus

Because Ca and P play important roles in the mineralization of bone, deficiency of either of these minerals results in weak and easily fractured bones (Veum, 2010). This is more evident in heavier animals, which tend to break their legs if insufficient quantities of P or Ca is fed; whereas, young growing pigs tend to develop rickets, which results in bending of the legs (Cromwell, 2005; NRC, 2012). Less visible symptoms of Ca or P deficiency include irregularity of the growth plate of the bone, diminished growth rate, poor feed utilization, and reduced leanness of the carcass. Posterior paralysis has been observed in lactating sows that were fed diets with inadequate amounts of Ca or P (Cromwell, 2005; NRC, 2012).

PHOSPHORUS IN FEED INGREDIENTS

Phosphorus nutrition has been studied more intensely than any other mineral element due to its high cost (Kiarie and Nyachoti, 2010). Plant ingredients, inorganic supplements, and animal-origin ingredients are the main sources of P in swine diets (NRC, 2012). Tables 2.2, 2.3, and 2.4 include P concentration and the STTD of P of the main ingredients used in swine nutrition.

Plant Ingredients

Plant ingredients used in swine nutrition are mainly grains and oilseeds, but coproducts from oilseeds and grains are also used. Some part of the grain may be removed before feeding; i.e., hulls and oil from the soybean. The concentration of P on a dry matter basis of oilseed meals is 5.7 to 12.0 g/kg; whereas, for cereals the concentration is 2.3 to 4.1 g/kg and for grain byproducts, the concentration of P is 8.0 to 27.0 g/kg (Kiarie and Nyachoti, 2010).

Corn, one of the most used ingredients in diets for swine, has a concentration of P of approximately 0.23% with a STTD of P of 39% on average (Almeida and Stein, 2012; NRC, 2012; Rojas et al., 2013; Casas and Stein, 2015). The concentration of P in sorghum is approximately 0.29% and the STTD of P in sorghum is 39% (Nyannor et al., 2007; NRC, 2012; Espinosa et al., 2019). Wheat, rye, and barley have a greater concentration of P and a greater STTD of P (NRC, 2012; Veum and Raboy, 2016) than corn. In contrast, rice and rice co-products have a greater concentration of P, but a lower STTD of P, except for broken rice, which has a lower concentration of P, but a greater STTD of P, than corn (NRC, 2012; Casas and Stein, 2015). However, in rice co-products, more than 65% of P is phytate-bound, which means that it

will be unavailable to the animal if there is no exogenous phytase included in the diet (Kiarie and Nyachoti, 2010).

Phytate. Phytic acid, also known as phytate (**IP_6**) or, myo-inositol heakis-phosphate, is the main form of P in plant ingredients. The main function of IP_6 in the plant is to serve as a reservoir of P to be used during different growth stages, and 50 to 80% of the total P in plants is bound to phytate (Ravindran, 1995). Inositol phosphate is present in most feed ingredients as IP_6 (90 - 95% of total phytate) with small amount of IP_5 and IP_4 esters (Morales et al., 2016). Due to its chemical structure, phytate is a very stable molecule with a high negative charge at a wide pH range (Morales et al., 2016), which allows the molecule to form complexes in physiological conditions to multivalent cations such as zinc (Zn^{2+}), cooper (Cu^{2+}), manganese (Mn^{2+}), Ca^{2+}, and iron (Fe^{2+}), decreasing the digestibility of these minerals (Cheryan and Rackis, 1980). Besides the effect of IP_6 on P and other minerals, results of several studies indicate that there are also interactions between phytate and AA, and AA digestibility may, therefore, also be reduced by phytate (Morales et al., 2016).

Phytase. Phytase, also known as myo-inositol hexakisphosphate phosphohydrolase, is the enzyme that catalyses the release of phosphate from IP_6 (Morales et al., 2016). Although, this enzyme is present in some of the plant ingredients used in swine diets such as wheat, rye and, triticale, the amounts present are insufficient to hydrolyze all the IP_6 in most diets. For other ingredients such as maize, legume seeds, and oilseed meals, the amount of phytase is low and hardly detectable (Rodehutscord and Rosenfelder, 2016). Nevertheless, intrinsic phytase can contribute to the breakdown of IP_6 in the gastrointestinal tract of animals, assuming that the enzyme was not deactivated or destroyed in the process of manufacturing and processing the feed (Rodehutscord and Rosenfelder, 2016).

There is a small presence of endogenous phytase in the gastrointestinal tract of pigs and poultry (Kiarie and Nyachoti, 2010), which is produced by the mucosa or microbiota colonizing the digestive tract (Rodehutscord and Rosenfelder, 2016). However, the quantitative relevance of the phytase produced in the small intestine has not been elucidated, and the synthesis of most microbial phytase occurs in the large intestine, where P cannot be absorbed because P is absorbed only in the small intestine of pigs. Therefore, the breakdown of IP_6 in the large intestine is irrelevant to the supply of P to the animal (Rodehutscord and Rosenfelder, 2016).

Exogenous microbial phytase has been used since 1971 to increase the availability of phytate-bound nutrients (Lei et al., 1993). This practice has been implemented in the industry by including approximately 500 units of phytase per kg, usually from *Aspergillus niger* or *Escherichia coli*, to hydrolyze approximately 50% of the phytate P in the diet (Dersjant-Li et al., 2015). However, studies have been conducted where the inclusion of phytase is greater than 500 units per kg, resulting in a greater digestibility of P and in release of more than 60% of phytate-bound P (Adeola et al., 2004; Mesina et al., 2018; She et al., 2018; Arredondo et al., 2019).

Animal Origin Ingredients

Since the development of the corn-soybean meal diet, the use of animal origin ingredients in swine diets has been reduced and mainly concentrated in diets for weaning pigs (Thacker, 1999). Plant based diets can deliver the required quantities of nutrients for growing-finishing pigs with the adequate supplementation of vitamins, minerals, and crystalline amino acids (Easter and Baker, 1980; Hahn et al., 1995).

Fish meal, meat and bone meal, blood meal, and co-products of milk are the main animal origin ingredients that are used in diets fed to weanling pigs. Because the P in animal origin

ingredients it is not bound to phytate, it is highly available to pigs (Kiarie and Nyachoti, 2010). Table 2.3 presents the P concentrations and STTD of P of the main animal origin ingredients used in swine diets.

Feed Phosphates

To meet the requirements for P of growing pigs, inorganic sources of P are included in the diets in addition to the P contributed by plant and animal origin ingredients (Jongbloed et al., 1991). Feed phosphates are products of the wet processing crushing of phosphate rock from volcanic or sedimentary origin, and after reaction with sulfuric acid, P is extracted from the rock and released in the form of phosphoric acid (Leikam and Achorn, 2005; Stewart et al., 2005). This product then goes through a second reaction with a source of another mineral, such as calcium carbonate in the case of production of monocalcium phosphate (**MCP**) or dicalcium phosphate (**DCP**; Speight, 2017).

The most widely used feed phosphates in swine diets are MCP and DCP (Petersen et al., 2011), but, monosodium phosphate (**MSP**) and magnesium phosphate (**MgP**) can be used as well (O'Connor et al., 1988; Cromwell et al., 1993).

Dicalcium Phosphate and Monocalcium Phosphate

Dicalcium phosphate and MCP are produced by the same process. After the reaction of phosphoric acid with a source of Ca (usually calcium carbonate or hydroxide) dicalcium phosphate is obtained (Freitas and Giulietti, 1997). The reaction of these two ingredients will naturally reach a chemical equilibrium that results in a mixture of DCP and MCP (Baker, 1989; Gard, 2005) and then, after reaching a concentration of P of 18.5%, the product is considered

DCP but if the concentration of P is equal to or greater than 21% the product is considered MCP (Baker, 1989).

Although the process of producing feed grade MCP and DCP is designed to eliminate impurities that may be harmful to animals, such as Al, As, Cd, and Pb other minerals are usually present in feed phosphates. These minerals include ferrous phosphate ($FePO_4 + 2H_2O$), magnesium phosphate [$Mg(H_2PO_4)_2 + 4H_2O$], aluminum phosphate ($AlPO_4$), and others (Baker, 1989).

Monosodium Phosphate

Monosodium phosphate is produced from the reaction of phosphoric acid and sodium hydroxide or carbonate, and it is the feed phosphate produced in the largest quantity (Gard, 2005). The concentration of P in MSP is above 25% and the digestibility of P in MSP is greater than the digestibility in other feed phosphates (NRC, 2012; González-Vega et al., 2015b; Kwon and Kim, 2017), and MSP is, therefore often considered the ideal standard used in experiments aimed to determining the relative bioavailability of P in feed ingredients (Weremko et al., 1997; Spencer et al., 2000; Petersen et al., 2011).

Magnesium Phosphate

Magnesium phosphate is also used in animal nutrition, especially in ruminants, because deficiency of Mg is more common in diets for ruminants. Magnesium phosphate is highly soluble (Gard, 2005) and has high digestibility, and the concentration of P is around 19% (NRC, 2012).

ABSORPTION OF PHOSPHORUS

Phosphorus is absorbed in the inorganic form (phosphate) mainly in the duodenum and jejunum (Gropper et al., 2009). Although results of some studies indicate absorption of P may also take place in the rumen of ruminants and in the cecum of swine (Veum, 2010). Phosphorus from animal ingredient sources tends to be absorbed in the upper section of the small intestine; whereas, phosphorus from plant ingredient sources is absorbed in the lower section (Gropper et al., 2009). Absorption of P occurs by active transport that can be saturated and depends on Na, or by facilitated diffusion, which is the quantitatively most important route of absorption (Gropper et al., 2009).

Relative Availability

Relative availability of nutrients is a measure that estimates the absorbed proportion of that nutrient that can be used by the animal (Stein et al., 2007). To estimate relative bioavailability a standard substance is used, and a test source of the same nutrient is used to conduct bioavailability assays such as slope ratio, standard curve, mean ratio comparison, or the three-point comparison (Littell et al., 1995). To estimate the relative bioavailability of P, MSP is most often used as the standard because of the high digestibility of P in MSP, and ash content in bone, bone strength, or P in serum are evaluated to determine the value of relative bioavailability (Weremko et al., 1997; Spencer et al., 2000; Petersen et al., 2011). However, a bioavailability assay implies the use of several treatments; therefore, more diets have to be formulated and more pigs have to be used. Moreover, to see results in the variable responses such as bone strength, the assays have to be longer than digestibility assays (Stein et al., 2007).

Digestibility

Digestibility is defined as the degree of disappearance of a nutrient after going through the gastrointestinal tract (Stein et al., 2007). It can be expressed as duodenal, ileal, or total tract digestibility, and may be calculated by subtracting the amount of nutrient excreted by the animal from the amount of nutrient ingested, and then divided by the amount of nutrient ingested (Stein et al., 2007). The values obtained from this calculation have to be considered apparent digestibility. Calculation of apparent digestibility assumes that the output of the nutrient comes entirely from the undigested portion of the food that was ingested by the animal. However, there is endogenous losses of most nutrients that originate from the gastrointestinal tract as a result of the natural process of digestion, and these losses may be basal endogenous losses or diet specific endogenous losses (Stein et al., 2007). Inclusion of the endogenous losses in the calculations of digestibility is accomplished by subtracting endogenous losses from the intake of the nutrient. This allows for calculation of the standardized or true digestibility of the nutrient (NRC, 2012).

There are no significant differences in values for apparent ileal digestibility (**AID**) of P and apparent total tract digestibility (**ATTD**) of P, because the absorption occurs in the small intestine with no measurable net absorption from the hindgut (Bohlke et al., 2005; NRC, 2012). Because experimental trials to estimate AID are more expensive and complex than those that estimate ATTD, digestibility values for P are based on ATTD, which can be calculated using the following equation (Almeida and Stein, 2010):

$$\text{ATTD of P (\%)} = [(\text{P ingested} - \text{P in feces}) / \text{P ingested}] \times 100$$

Although the endogenous P loss is relatively small (NRC, 2012), it is necessary to do a correction for this loss to estimate the STTD of P. The endogenous P loss can be calculated by feeding a P-free diet and using the following equation (Almeida and Stein, 2010):

$$\text{Endogenous P loss (mg/kg dry of matter intake)} = [(\text{P in feces/dry matter intake}) \times 1{,}000 \times 1{,}000]$$

By using the value for endogenous P loss to correct ATTD values, the STTD of P is calculated using the following equation (Almeida and Stein, 2010):

$$\text{STTD of P (\%)} = \{[\text{P ingested} - (\text{P in feces} - \text{endogenous P loss})] / \text{P ingested}\} \times 100$$

Values for STTD of P in ingredients are additive in mixed diets, and therefore, STTD values need to be used in diet formulation (NRC, 2012; She et al., 2018).

CONCLUSIONS

Phosphorus is the most expensive macro mineral in swine nutrition and is needed for bone mineralization and in several metabolic pathways. Feed phosphates are included in most diets because P is deficient in most plant ingredients used to formulate diets for pigs. Requirements for P by pigs in different stages of production have been determined and the digestibility of P in most ingredients used in swine diets has been reported. The use of phytase increases the digestibility of P in plant ingredients, but even with phytase in the diet supplementation with P from feed phosphates is needed in most diets. The main feed phosphates used in swine diets, are MCP, DCP, and MSP. The raw material used to produce feed phosphates may originate from different rock deposits, which may affect the concentration of P and other minerals in feed phosphates. It is also possible that the origin of the rock phosphate influences the digestibility of P, but data to demonstrate this have not been reported. Therefore, more

research is needed to determinate if there are significant differences among feed grade phosphates produced from different sources.

TABLES

Table 2.1. Phosphorus requirements of swine (Cromwell, 2005; NRC, 2012)

Stage	P (%)	STTD[1] of P (%)	P (g/day)	STTD P (g/day)
Growing Pigs				
5-7 kg	0.70	0.45	1.86	1.20
7-11 kg	0.65	0.40	3.04	1.87
11-25 kg	0.60	0.33	5.43	2.99
25-50 kg	0.56	0.31	8.47	4.59
50-75 kg	0.52	0.27	10.92	5.78
75-100 kg	0.47	0.24	11.86	6.11
100-135 kg	0.43	0.21	11.97	5.95
Gestation sows				
Parity 1				
<90 days	0.49	0.27	9.91	5.40
>90 days	0.62	0.36	14.78	8.67
Parity 2				
<90 days	0.45	0.24	9.40	4.96
>90 days	0.58	0.34	14.45	8.39

Table 2.1. (Cont.)

Parity 3				
<90 days	0.41	0.21	8.67	4.43
>90 days	0.55	0.31	13.59	7.79
Parity 4 +				
<90 days	0.38	0.19	7.98	3.93
>90 days	0.52	0.29	12.75	7.20
Lactation sows				
Parity 1	0.56	0.31	31.6	17.7
Parity 2 +	0.54	0.30	34.1	18.9
Boars	0.75	0.33	17.81	7.84

[1]STTD = standardized total tract digestibility; STTD P = standardized total tract digestible P

Table 2.2. Phosphorus concentration in feed plant ingredients used in swine nutrition[1]

Ingredient	P, (%)	STTD of P, (%)	References
Cereal grains and by-products			
Barley	0.36	45.00	NRC (2012); Veum and Raboy (2016)
Corn	0.23	39.13	NRC (2012); Almeida and Stein (2012); Rojas et al. (2013); Casas and Stein (2015)
Corn DDGS, >10% oil	0.82	68.20	NRC (2012); Almeida and Stein (2012); Baker et al. (2013); Rojas et al. (2013)
Rice	0.34	33.00	NRC (2012)
Rice bran	1.98	25.95	NRC (2012); Casas and Stein (2015)
Rice bran, defatted	2.24	31.70	NRC (2012); Casas and Stein (2015)
Rice, broken	0.16	45.75	NRC (2012); Casas and Stein (2015)
Rye	0.29	50.75	NRC (2012); McGhee and Stein (2019)
Sorghum	0.29	39.27	Nyannor et al. (2007); NRC (2012); Espinosa et al. (2019)

Table 2.2. (Cont.)

Sorghum DDGS	0.74	-	NRC (2012); Sotak et al. (2014)
Triticale	0.33	56.00	NRC (2012)
Triticale DDGS	0.70	68.20	NRC (2012); Xue and Adeola (2015)
Oats	0.35	39.00	NRC (2012)
Wheat, hard red	0.39	56.00	NRC (2012)
Wheat, soft red	0.30	56.00	NRC (2012)
Wheat bran	0.99	56.00	NRC (2012)
Wheat DDGS	0.92	61.00	NRC (2012)
Wheat middlings	0.98	56.00	NRC (2012)
Oilseed meals			
Canola meal, expelled	1.15	32.00	NRC (2012)
Canola meal, solvent extracted	1.08	45.05	Akinmusire and Adeola (2009); NRC (2012); Rodríguez et al. (2013); Maison et al. (2015); She et al. (2017)
Cottonseed meal	1.14	40.80	NRC (2012); Rodríguez et al. (2013)
Cottonseed meal, full fat	0.65	36.00	NRC (2012)

Table 2.2. (Cont.)

Soybean meal, dehulled, solvent extracted	0.66	50.77	Akinmusire and Adeola (2009); NRC (2012); Rojas and Stein (2012); Oliveira and Stein (2016)
Soybean meal,	0.80	66.00	NRC (2012)
Soybean meal, enzyme treated	0.75	66.00	NRC (2012)
Soybean meal, fermented	0.79	65.75	NRC (2012); Rojas and Stein (2012)
Sunflower meal, dehulled, solvent extracted	1.22	39.50	NRC (2012); Rodríguez et al. (2013)
Pulses			
Field peas	0.42	56.00	NRC (2012)
Faba beans	0.42	36.00	NRC (2012)

[1]STTD = standardized total tract digestibility; Values for concentration and STTD of P are an average of reported values.

Table 2.3. Phosphorus concentration in animal origin feed ingredients used in swine nutrition[1]

Ingredient	P, (%)	STTD of P, (%)	References
Meat and bone meal	4.78	69.38	NRC (2012); Sulabo and Stein (2013)
Meat meal	3.16	86.00	NRC (2012)
Blood meal	0.21	88.00	NRC (2012)
Blood plasma	1.28	98.00	NRC (2012)
Fishmeal	3.17	72.60	NRC (2012); Sulabo et al. (2013); González-Vega et al. (2015a)
Milk products			
Casein	0.63	98.00	NRC (2012); González-Vega et al. (2015a)
Whey powder	0.66	91.60	NRC, 2012; Kim et al. (2012)

[1]STTD = standardized total tract digestibility; Values for concentration and STTD of P are an average of reported values.

Table 2.4. Phosphorus concentration in inorganic ingredients used in swine nutrition[1]

Ingredient	P, (%)	STTD of P, (%)	References
Dicalcium phosphate	19.09	87.25	NRC (2012); Baker et al. (2013); González-Vega et al. (2015b); Kwon and Kim (2017); Lee et al. (2019)
Monocalcium phosphate	22.28	90.65	NRC (2012); González-Vega et al. (2015b); Kwon and Kim (2017)
Tricalcium phosphate	18.90	62.35	NRC (2012); Kwon and Kim (2017)
Magnesium phosphate	19.70	98.20	NRC (2012)
Sodium phosphate, monobasic	25.45	94.35	NRC (2012); González-Vega et al. (2015b); Kwon and Kim (2017)
Phosphate rock, soft	9.05	-	NRC (2012)

[1]STTD = standardized total tract digestibility; Values for concentration and STTD of P are an average of reported values.

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CHAPTER 3: MINERAL COMPOSITION IN COMMERCIALLY AVAILABLE FEED PHOSPHATES

ABSTRACT

Seven sources of monocalcium phosphate (**MCP**), 4 sources of dicalcium phosphate (**DCP**), 2 sources of monosodium phosphate (**MSP)**, and 1 source of magnesium phosphate (**MgP)** were procured for a total of 14 commercial feed phosphates. The 14 sources were analyzed for dry matter (**DM),** ash, macro minerals (Ca, P, Mg, Na, K, and S), micro minerals (Co, Cu, Fe, Mn, and Zn), and minerals that can be harmful (Al, As, Cd, F, Hg, Pb, and Si). The percentage of P and Ca bound to the possible impurities in MCP and DCP were calculated. Concentrations of DM, ash, and macro minerals were not different within each source of feed phosphate, but MgP contained more S than the other feed phosphates. The concentrations of micro minerals and possible harmful minerals were more variable within each source of feed phosphate, but the proportion of P and Ca bound to impurities in MCP and DCP was not different among sources. In conclusion, the process of production of feed phosphates is effective in generating products with a specified concentration of P and a low concentration of potentially harmful minerals.

Key words: feed phosphates, impurities, macro minerals, micro minerals

INTRODUCTION

Feed grade phosphates are added to diets for animals to meet the requirements for P due to the low digestibility of P in plant ingredients (Kiarie and Nyachoti, 2010; NRC, 2012). The process of production of feed phosphates begins with the mining of rock phosphate from either igneous (volcanic) or sedimentary origin (Leikam and Achorn, 2005; Stewart et al., 2005).

Following extraction of the rock phosphate, it is crushed and goes through a process called beneficiation (Stewart et al., 2005). The resulting material is then reacted with sulfuric acid to produce phosphoric acid (Al-Fariss et al., 1992). A second reaction in which phosphoric acid is reacted with another mineral is needed to produce feed phosphates (Speight, 2017). In most cases, the second mineral is calcium carbonate and reacting phosphoric acid with calcium carbonate first results in production of dicalcium phosphate (**DCP**). However, if more phosphoric acid is added, the reaction continues and monocalcium phosphate (**MCP**) is produced (Gard, 2005). The concentration of P in volcanic phosphate ores may be low, but it can be used to produce rock phosphate with higher concentration of P; whereas, the concentration of P in rock phosphate from sedimentary sources varies depending on the amount of carbonate in the ore. Ores with a lower carbonate substitution can be used to produce rock phosphate that will have a greater amount of P than will be obtained from ores with greater carbonate substitution (Stewart et al., 2005).

Analytical grade DCP contains 22.8% P and 29.4% Ca, and analytical grade MCP contains 26.5% P and 17.1% Ca. However, feed grade DCP and MCP contain only 18.5 and 21.0% P, respectively, which likely is a result of impurities in feed grade DCP and MCP (Baker, 1989). Some of the minerals considered impurities can be bound to phosphate groups during production of feed phosphates, possibly reducing the bioavailability of P. Ores from both volcanic and sedimentary sources contain impurities (Lindgren, 1913; Leikam and Achorn, 2005), but the process of producing feed phosphates was developed to reduce the concentrations of those impurities, especially the concentration of potentially harmful minerals, in the final product (Lima et al., 1995; 1999). Therefore, the objective of this work was to test the hypothesis that the process to produce feed phosphates results in products that contain the specified

concentration of P and also removes most impurities and the remaining concentrations of potentially harmful impurities are less than what are tolerated by animals.

MATERIALS AND METHODS

Seven sources of MCP, 4 sources of DCP, 2 sources of MSP, and 1 source of MgP were procured from commercial producers for a total of 14 feed phosphates. A sample of each feed phosphate was collected and stored at -20 ^{o}C prior to analyses. All samples were analyzed for P, Ca, Cu, Fe, K, Mg, Mn, Na, S and Zn using Inductively Coupled Plasma-Optical Emission Spectrometry (**ICP-OES**, method 2011.14; AOAC, 2007) and Co was also analyzed using ICP-OES (method 2006.03; AOAC, 2007). For the analysis of As, Cd, and Pb, samples were analyzed using Inductively Coupled Plasma-Mass Spectrometry (**ICP-MS**: method 2015.01; AOAC, 2007), and Hg was analyzed by Atomic Absorption Spectroscopy (method 971.21; AOAC, 2007). Samples were also analyzed for DM by oven drying at 135°C for 2 h (method 930.15; AOAC, 2007), for ash (method 942.05; AOAC, 2007), fluorine (method 905.03; AOAC, 2007), aluminum (method 990.08; AOAC, 2007), silicon (method 920.08; AOAC, 2007), and free water (method 965.08; AOAC, 2007).

Based on the concentrations of analyzed minerals, the concentrations of silica, calcium fluoride, calcium sulfate, calcium carbonate, ferrous phosphate, aluminum phosphate, magnesium phosphate, and sodium phosphate were calculated (Baker, 1989). To calculate the percentage of P bound to impurities in the total P from each feed phosphate, the first step was to calculate the amount of molecules of P and other minerals present in the phosphates. This was

achieved by dividing the mass in grams of each mineral by the molar mass of the mineral, using the following equation (Tro et al., 2013):

$$\text{Mol} = \left(\frac{\text{grams of mineral}}{\text{Molar mass}} \right) \times \text{Avogadro constant}$$

where Mol represents the number of molecules of a mineral in the feed phosphate, grams of mineral is the mass of the mineral analyzed from each feed phosphate, and molar mass is the molecular weight that was obtained from the periodic table of elements.

The second step was to determine the possible impurities in the feed phosphates, and the chemical formula of those impurities (Table 3.1), which allowed for calculation of how many molecules of P are present in each impurity compound (e.g., from the formula of ferrous phosphate it is assumed that one atom of P and one atom of Fe are present). This relationship was used to calculate the percentage of P bound to a specific impurity compound. The following equation was used to calculate the percentage of P bound to a specific impurity compound:

$$\%\ \text{P bound} = [(\text{Mol/P:M})/\text{Mol of P}\ ] \times 100$$

where Mol represents the number of molecules of the main mineral in the impurity compound, P:M represents the relationship of P and the main mineral in the impurity compound, and MolP is the number of molecules of P in the feed phosphate.

To calculate the amount of P bound to the compounds as gram per kilogram of feed phosphate, the following equation was used:

$$\text{P bound (g/kg)} = \left(\frac{\text{g of P} \times \ \%\ \text{of P bound to impurity compound}}{100} \right)$$

where grams of P is the mass of P in the feed phosphate, and percentage of P bound to impurity compound is the value calculated with the previous equation.

RESULTS AND DISCUSSION

The concentration of DM in all samples was greater than 90%; whereas, the concentration of ash was greater than 78% (Table 3.2), which is in agreement with previous data (Lima et al., 1999; Souza et al., 2009; González-Vega et al., 2016a; 2016b; Lagos et al., 2019a, b; Lee et al., 2019). The difference between DM and ash may be attributed to the wet process used to produce phosphoric acid. In this process, the sulfuric acid used to extract phosphoric acid from phosphate rock, is diluted in water (Lima et al., 1995; 1999). However, feed phosphates with a lower difference between DM and ash may be produced if the thermal process is used (Lima et al., 1995; 1999). The loss of weight after the analysis of ash represents the loss of water of crystallization, carbon dioxide, and volatile minerals (Lima et al., 1995; 1999). Crystalized water originates from some of the phosphate salts that are present in feed phosphates; whereas, carbon dioxide is lost from carbonates.

In pure sources of MCP, DCP, MSP, and MgP, concentrations of P are 26.47, 22.77, 25.80, and 28.33, respectively (Table 3.3). However, feed grade sources of these ingredients have lower concentrations of P, but all samples of MCP and DCP had concentrations of P (i.e., 21.0 and 18.5%) that are adequate to be considered feed grade MCP and feed grade DCP, respectively (Baker, 1989). Values are also in agreement with previously reported data (Lima et al., 1995; 1997; 1999; Souza et al., 2009; NRC, 2012; González-Vega et al., 2016a; 2016b; Lagos et al., 2019a, b; Lee et al., 2019). The reason for this observation likely is that producers

of DCP and MCP have to guarantee a minimum concentration of P in the final products, which is controlled by the amount of phosphoric acid that is added to calcium carbonate and the reaction is usually stopped when the desired concentration of P is achieved.

The concentration of P in MSP is in agreement with previously reported data (Souza et al., 2009; NRC, 2012; González-Vega et al., 2015; Kwon and Kim, 2017); whereas, the concentration of P in MgP was lower than reported values (NRC, 2012). Magnesium is usually not added to practical diets for pigs, but MgP is sometimes used in mineral premixes if feed ingredients with low availability of Mg are used (NRC, 2012). Requirements for Na can be met by inclusion of salt in the diets, which also will result in Cl meeting the requirement (NRC, 2012); MSP is therefore, rarely used as a source of Na in practical diets. Concentrations of Na and Mg in the sources of MCP and DCP used in this work are in agreement with previous data (Lima et al., 1999; Souza et al., 2009). Concentrations of K and S in the feed phosphates were also in agreement with reported data (Lima et al., 1999), but MgP had a concentration of S that was considerably greater than in all other feed phosphates. However, even if MgP is used to provide the majority of P in diets, the concentration of S will be less than the concentration that is expected to negatively affect growth of the animal due to the low inclusion of feed phosphates in the final diets and the relatively low absorption of inorganic S in the pig (McGlone and Pond, 2003; NRC, 2012). Microminerals such as Co, Cu, Fe, Mn, and Zn were present in MCP and DCP in concentrations that were in agreement with previous data (Lima et al., 1999; Souza et al., 2009).

In addition to the minerals that have a nutritional value, As, Cd, Pb, and Hg were also analyzed. These minerals are considered possibly harmful for the animal (NRC, 2012). However, all sources analyzed had concentrations of these minerals that can be considered safe to animals

(Lima et al., 1995; 1999), and the concentrations of these potentially harmful minerals were in agreement with published data (Lima et al., 1999; Souza et al., 2009). Concentrations of Al, which is another potentially harmful mineral, were low in the samples analyzed in this work compared with previously reported data (Lima et al., 1999; Souza et al., 2009).

Within sources of MCP, DCP, and MSP, a low variability of DM, ash, Ca, P, Mg, Na, K, and S was observed (Table 3.4). These values indicate a homogeneous concentration of minerals that are meant to be delivered by the feed phosphate (i.e., Ca and P in MCP and DCP and Na and P in MSP). The low variability in concentrations of macro minerals is desirable because each mineral has to be included in diets in specific amounts in the form of premixes. In contrast, concentrations of micro minerals such as Co, Cu, Fe, and Zn were more variable in MCP and DCP; whereas for MSP, most micro minerals except Zn were undetectable. This observation indicates that the majority of impurities in MCP and DCP likely are provided by calcium carbonate, which is not used in the production of MSP. Micro minerals also have to be included in diets, but in smaller concentrations than macro minerals, which may represent a problem if feed phosphates have variable concentrations of these nutrients. However, the inclusion of feed phosphates in animal diets is low, and because the concentrations of these minerals is low as well, the concentration of micro minerals in feed phosphate is unlikely to have a major influence on the concentration of micro minerals in the final diet. Concentrations of F and Mn were less variable than concentrations of other minerals. The production of feed phosphates includes a process of de-fluorination (Leikam and Achorn, 2005), which likely is the reason for the low concentrations of F in all sources of MCP, DCP, MSP, and MgP. In the case of potentially harmful minerals analyzed, for MCP, DCP, and MSP, the concentration of Al, As, Cd, Pb, and Si, was highly variable among and within sources. However, because all feed phosphates had

concentration of these minerals under harmful levels for the animals, these variations are unlikely to influence animal performance.

Some of the minerals considered impurities in feed phosphate such as Fe, Al, Mg, and Na can form phosphate salts (Baker, 1989). The digestibility of P in MCP is often greater than in DCP (Petersen and Stein, 2006; NRC, 2012) and a greater proportion of MCP in the feed phosphate is, therefore, desirable. Because P can be bound to different minerals in feed grade MCP and DCP, theoretically, the proportion of the P that is bound to other minerals can be calculated if the concentration of those minerals is known (Tables 3.5 and 3.6). If it is assumed that there is 10% DCP in MCP, 14 % MCP in DCP, and 1% unreacted phosphoric acid in MCP (Baker, 1989; Gard, 2005) all P in MCP and DCP can be accounted for. Phosphorus bound to impurities and other phosphate salts in MCP varied between 3.2% and 10.8%; whereas, in DCP, the P bound to minerals other than DCP varied between 3.8% and 8.0%. After the proportion of P bound to impurities and to DCP in MCP sources was substracted from the total P concentration, the P bound in molecules of MCP was constant among the 7 sources used in this work. The digestibility of P in MCP and DCP has been reported (Petersen and Stein, 2006; NRC, 2012) but it is not clear if the P bound to the other phosphate salts are as digestible as P bound in MCP. Because the overall digestibility of P in feed phosphates is high, it is assumed that all sources of P have high digestibility. In the 4 sources of DCP, the percentage of P bound to DCP was also constant among sources if the water in hydrated DCP was taken into account.

The proportion of Ca bound to impurities was calculated as well (Tables 3.7 and 3.8), assuming 10% DCP in MCP and 14% MCP in DCP, and 6.7% calcium carbonate in DCP (Baker, 1989; Gard, 2005). For MCP sources, the percentage of Ca bound to impurities ranged from 2.8% to 18.7%; whereas, the Ca bound to impurities in DCP ranged from 13.21% to

17.14%. However, a high proportion of the Ca bound to impurities in both MCP and DCP is present in the form of calcium carbonate, which is also highly digestible for animals. The reason for the presence of calcium carbonate in MCP and DCP is that in the production of these phosphates, phosphoric acid is reacted with calcium carbonate and the reaction is stopped when the desired concentration of P is achieved. As a consequence, the amount of calcium carbonate that is reacted with phosphoric acid depends on the purity of the product and residual calcium carbonate that is unreacted will contribute to the Ca concentration in the final product. This is the reason the Ca concentration in MCP and DCP is variable.

CONCLUSIONS

The process to produce feed phosphate results in final products that meet the minimum concentration of P, but it also results in products with low concentrations of possible harmful minerals. Differences in impurities and how P or Ca are bound may influence the digestibility of P in feed phosphates.

TABLES

Table 3.1. Impurities and composition in commercial feed grade phosphate[1,2]

Component, %	Chemical formula	DCP (18.5% P)	MCP (21.0% P)
Minerals not containing P			
Silica	SiO_2	0.15	0.13
Calcium fluoride	CaF_2	0.32	0.44
Calcium sulfate	$CaSO_4 \cdot H_2O$	3.51	3.95
Free water	H_2O	0.80	1.00
Calcium carbonate	$CaCO_3$	6.74	6.00
Minerals containing P			
Ferrous phosphate	$FePO_4 \cdot H_2O$	2.65	2.98
Aluminum phosphate	$AlPO_4$	2.21	2.48
Magnesium phosphate	$Mg(H_2PO_4)_2 \cdot 4H_2O$	7.02	7.89
Sodium phosphate	$NaH_2PO_4 \cdot 2H_2O$	0.54	0.61
Phosphoric acid	H_3PO_4	0.80	1.00
MCP and DCP composition			
Monocalcium Phosphate	$Ca(H_2PO_4)_2 \cdot H_2O$	14.19	60.98
Dicalcium Phosphate	$CaHPO_4$	26.42	12.54
Hydrated Dicalcium Phosphate	$CaHPO_4 \cdot 2H_2O$	34.65	-

[1]MCP = monocalcium phosphate; DCP = dicalcium phosphate.

[2]Values are adapted from Baker (1989)

Table 3.2. Dry matter, ash and mineral composition of feed phosphates[1]

Item	MCP1	MCP2	MCP3	MCP4	MCP5	MCP6	MCP7	DCP1	DCP2	DCP3	DCP4	MSP1	MSP2	MgP1
DM, %	92.6	93.7	92.6	93.1	93.6	93.7	91.4	95.2	94.0	94.9	95.6	98.8	99.6	96.6
Ash, %	80.2	80.5	79.2	79.8	79.1	79.5	78.6	85.5	81.7	82.5	83.5	85.2	91.3	86.4
Ca, %	16.6	17.2	16.6	16.7	16.0	16.2	17.3	23.9	18.9	18.9	23.5	1.1	0.2	1.0
P, %	23.0	21.0	23.4	21.4	21.1	21.7	21.8	18.7	19.5	19.3	19.2	23.7	27.6	14.8
Mg, %	1.2	0.7	0.5	0.3	1.5	0.3	0.7	0.8	0.2	1.5	0.3	0.8	<0.1	24.7
Na, %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.2	<0.1	<0.1	0.2	<0.1	20.5	20.5	0.7
K, %	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	<0.1	0.1
S, %	<0.1	0.1	<0.1	0.3	0.2	0.3	0.2	0.7	0.3	0.2	0.2	<0.1	<0.1	1.7
Al, mg/kg	60.6	958.0	20.3	370.0	1,380	268.0	3.1	<2.0	482.0	1,140	38.3	1,580	668.0	161.0
As, mg/kg	2.7	13.0	2.5	7.1	5.8	5.8	5.1	4.3	6.2	4.4	7.9	1.6	0.4	1.0
Cd, mg/kg	0.3	3.1	7.1	3.9	0.2	3.1	6.6	6.9	3.0	0.2	2.4	0.2	0.4	0.2
Co, mg/kg	4.7	2.0	0.6	6.5	1.0	5.0	0.9	0.7	5.5	1.0	5.0	4.0	<0.5	4.0
Cu, mg/kg	1.0	13.0	11.0	5.6	0.9	6.5	23.0	19.0	5.9	1.0	5.0	0.6	<0.5	2.0
F, %	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.1	<0.1	0.1

Table 3.2. (Cont.)

Fe, %	0.5	0.8	0.2	1.3	0.4	1.2	0.1	0.1	1.3	0.3	1.1	0.4	<0.10	0.3
Hg, mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Mn, %	<0.1	<0.1	<0.1	0.1	<0.1	0.1	<0.1	<0.1	0.1	<0.1	0.1	<0.1	<0.1	<0.1
Pb, mg/kg	1.3	3.8	0.2	0.9	0.9	0.8	0.2	0.3	0.8	1.0	1.1	0.1	<0.1	0.2
Si, mg/kg	3,020	7,020	551.0	3,360	5,700	3,030	1,790	575.0	2,520	4,700	4,840	414.0	361.0	17,300
Zn, mg/kg	75.0	160.0	250.0	83.0	32.0	74.0	190.0	200.0	75.0	30.0	51.0	55.0	1.0	50.0
Free H_2O, %	0.2	0.1	0.9	0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	1.4	<0.1	<0.1	<0.1

[1]MCP= monocalcium phosphate; DCP= dicalcium phosphate; MSP= monosodium phosphate; MgP= magnesium phosphate.

Table 3.3. Molecular weight and percentage composition of pure feed phosphates[1]

	Total molecular mass (g/mol)	Percentage (%)
DCP [$CaHPO_4$]		
Ca × 1	40.08	29.46
H × 1	1.01	0.74
P × 1	30.97	22.77
O × 4	64.00	47.04
Total	136.06	100.00
MCP [$Ca(H_2PO_4)_2$]		
Ca × 1	40.08	17.12
H × 4	4.03	1.72
P × 2	61.95	26.47
O × 8	128.00	54.69
Total	234.05	100.00
MSP [NaH_2PO_4]		
Na × 1	22.99	19.16
H × 2	2.02	1.69
P × 1	30.97	25.80
O × 4	64.00	53.3
Total	120.00	100.00
MgP [$Mg(H_2PO_4)_2$]		
Mg × 1	24.3	11.13
H × 4	4.03	1.85

Table 3.3. (Cont.)

P × 2	61.95	28.38
O × 8	128.00	58.64
Total	218.28	100.00

[1]MCP = monocalcium phosphate, MSP = monosodium phosphate, MgP = magnesium phosphate, DCP = dicalcium phosphate.

Table 3.4. Average and standard deviation of dry matter, ash and mineral composition of feed phosphates[1]

Item	MCP	DCP	MSP
DM, %	92.97 ± 0.78	94.91 ± 0.60	99.22 ± 0.41
Ash, %	79.55 ± 0.62	83.27 ± 1.41	88.26 ± 3.03
Macro minerals			
Ca, %	16.66 ± 0.44	21.30 ± 2.40	0.65 ± 0.45
P, %	21.91 ± 0.86	19.18 ± 0.28	25.65 ± 1.95
Mg, %	0.74 ± 0.42	0.70 ± 0.51	-
Na, %	-	-	20.50 ± 0.00
K, %	0.13 ± 0.02	0.12 ± 0.02	-
S, %	0.22 ± 0.07	0.35 ± 0.21	-
Micro minerals			
Co, mg/kg	2.96 ± 2.21	3.05 ± 2.21	-
Cu, mg/kg	8.71 ± 7.20	7.73 ± 6.77	-
Fe, %	0.64 ± 0.44	0.71 ± 0.50	-
Mn, %	0.04 ± 0.02	0.04 ± 0.02	-
Zn, mg/kg	123.43 ± 72.28	89.00 ± 66.03	28.00 ± 27.00
Other minerals			
Al, mg/kg	437.14 ± 492.14	553.43 ± 452.59	1,124 ± 456.00
As, mg/kg	6.00 ± 3.26	5.70 ± 1.48	1.00 ± 0.60
Cd, mg/kg	3.47 ± 2.52	3.13 ± 2.41	0.31 ± 0.08
F, %	0.15 ± 0.04	0.14 ± 0.02	-

Table 3.4. (Cont.)

Hg, mg/kg	-	-	-
Pb, mg/kg	1.16 ± 1.14	0.80 ± 0.30	0.08 ± 0.04
Si, mg/kg	3,496 ± 2,047	3,159 ± 1,753	387.50 ± 26.50
Free H_2O, %	0.29 ± 0.30	-	-

[1]MCP= monocalcium phosphate; DCP= dicalcium phosphate; MSP= monosodium phosphate; calculated values correspond to 7 MCP sources, 4 DCP sources and 2 MSP sources.

Table 3.5. Calculated P-including impurities of 7 sources of monocalcium phosphate (MCP)

	MCP1		MCP2		MCP3		MCP4		MCP5		MCP6		MCP7	
Item,	g/kg	%	g/kg	%	g/kg	%	g/kg	%	g/kg	%	g/kg	%	g/kg	%
Total P	229.90	100.00	210.00	100.00	234.00	100.00	214.00	100.00	211.00	100.00	217.00	100.00	218.00	100.00
Ferrous phosphate P	2.77	1.20	4.54	2.16	0.89	0.38	7.20	3.36	2.10	1.00	6.64	3.06	0.78	0.36
Aluminum phosphate P	0.07	0.03	1.10	0.52	0.02	0.01	0.42	0.20	1.58	0.75	0.31	0.14	-	-
Magnesium phosphate P	7.75	3.37	4.52	2.15	3.23	1.38	1.94	0.91	9.69	4.59	1.94	0.89	4.52	2.07
Sodium phosphate P	1.21	0.53	1.21	0.58	1.21	0.52	1.21	0.57	1.21	0.57	1.21	0.56	16.17	7.42
Phosphoric acid P[1]	2.01	0.87	2.01	0.96	2.01	0.86	2.01	0.94	2.01	0.95	2.01	0.93	2.01	0.92
Total P bound to impurities	13.81	6.01	13.38	6.37	7.36	3.15	12.78	5.97	16.60	7.87	12.11	5.58	23.48	10.77
Dicalcium phosphate P[2]	22.80	9.92	22.80	10.86	22.80	9.74	22.80	10.65	22.80	10.81	22.80	10.51	22.80	10.46
Monocalcium phosphate P[3]	193.29	84.08	173.82	82.77	203.84	87.11	178.42	83.37	171.60	81.33	182.09	83.91	171.72	78.77

[1]Calculated value assuming 1% of unreacted phosphoric acid (Baker, 1989).

[2]Calculated value assuming 10% DCP in the MCP sources (Gard, 2005).

[3]Calculated value assuming that the P not bound to any other compound is bound in monocalcium phosphate.

Table 3.6. Calculated P-including impurities of 4 sources of dicalcium phosphate (DCP)

	DCP1		DCP2		DCP3		DCP4	
Item,	g/kg	%	g/kg	%	g/kg	%	g/kg	%
Total P	187.00	100.00	195.00	100.00	193.00	100.00	192.00	100.00
Ferrous phosphate P	0.72	0.38	7.20	3.69	1.72	0.89	6.09	3.17
Aluminum phosphate P	-	-	0.55	0.28	1.31	0.68	0.05	0.02
Magnesium phosphate P	5.17	2.76	1.29	0.66	9.69	5.02	1.94	1.01
Sodium phosphate P	1.21	0.65	1.21	0.62	2.70	1.40	1.21	0.63
Total P bound to impurities	7.10	3.80	10.25	5.26	15.41	7.98	9.29	4.84
Monocalcium phosphate P[1]	34.44	18.42	34.44	17.66	34.44	17.84	34.44	17.94
Hydrated dicalcium phosphate P[2]	61.40	32.83	78.27	40.14	54.14	28.05	27.31	14.22
Dicalcium phosphate P[3]	84.06	44.95	72.03	36.94	89.01	46.12	120.97	63.00

[1]Calculated value assuming 14% MCP present in the DCP sources (Baker, 1989).

[2]Calculated value using the percentage of moisture of the sample discounting the percentage of free water.

[3]Calculated value assuming that the P not bound to any other compound it is bound to dicalcium phosphate.

Table 3.7. Calculated Ca-including impurities of 7 sources of monocalcium phosphate (MCP)

	MCP1		MCP2		MCP3		MCP4		MCP5		MCP6		MCP7	
Item,	g/kg	%	g/kg	%	g/kg	%	g/kg	%	g/kg	%	g/kg	%	g/kg	%
Total Ca	166.00	100.00	172.00	100.00	166.00	100.00	167.00	100.00	160.00	100.00	162.00	100.00	173.00	100.00
Calcium fluoride Ca	1.47	0.89	1.79	1.04	1.05	0.63	1.89	1.13	2.11	1.32	1.89	1.17	1.05	0.61
Calcium sulfate Ca	1.13	0.68	1.25	0.73	0.11	0.07	3.75	2.25	2.50	1.56	3.75	2.31	2.50	1.45
Calcium carbonate Ca	8.83	5.32	26.99	15.69	3.43	2.07	16.41	9.82	14.85	9.28	9.03	5.57	28.84	16.67
Total Ca bound to impurities	11.43	6.89	30.03	17.46	4.60	2.77	22.05	13.20	19.46	12.16	14.68	9.06	32.39	18.72
Dicalcium phosphate Ca[1]	29.50	17.77	29.50	17.15	29.50	17.77	29.50	17.66	29.50	18.44	29.50	18.21	29.50	17.05
Monocalcium phosphate Ca[2]	125.07	75.34	112.47	65.39	131.90	79.46	115.45	69.13	111.04	69.40	117.83	72.73	111.11	64.23

[1]Calculated value assuming 10% of DCP present in MCP sources (Gard, 2005).

[2]Calculated value assuming that the Ca unbound to any other compound it is bound to monocalcium phosphate.

Table 3.8. Calculated Ca-including impurities of 4 sources of dicalcium phosphate (DCP)

	DCP1		DCP2		DCP		DCP4	
Item,	g/kg	%	g/kg	%	g/kg	%	g/kg	%
Total Ca	239.00	100.00	189.00	100.00	189.00	100.00	235.00	100.00
Calcium fluoride Ca	1.05	0.44	1.68	0.89	1.58	0.84	1.58	0.67
Calcium sulfate Ca	8.75	3.66	3.75	1.98	2.50	1.32	2.50	1.06
Calcium carbonate Ca[1]	26.96	11.28	26.96	14.26	26.96	14.26	26.96	11.47
Total Ca bound to impurities	36.76	15.38	32.39	17.14	31.04	16.42	31.04	13.21
Monocalcium phosphate Ca[2]	22.26	9.31	22.26	11.78	22.26	11.78	22.26	9.47
Hydrated dicalcium phosphate Ca[3]	79.48	33.25	101.25	53.57	70.04	37.06	35.32	15.03
Dicalcium phosphate Ca[4]	127.46	53.33	60.06	31.78	92.62	49.01	173.34	73.76

[1]Calculated value assuming 6.7% of unreacted calcium carbonate in DCP sources (Baker, 1989)

[2]Calculated value assuming 14% of MCP present in the DCP sources (Baker, 1989).

[3]Calculated value using the percentage of moisture of the sample discounting the percentage of free water.

[4]Calculated value assuming that the Ca not bound to any other compound it is bound to dicalcium phosphate.

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CHAPTER 4: STANDARDIZED TOTAL TRACT DIGESTIBILITY BY GROWING PIGS OF P IN FEED PHOSPHATES FROM VOLCANIC AND NON-VOLCANIC SOURCES

ABSTRACT

An experiment was conducted to determine if the apparent total tract digestibility (**ATTD**) and the standardized total tract digestibility (**STTD**) of P in feed phosphates from volcanic (igneous) sources are greater than those produced from non-volcanic (sedimentary) sources. Sources of monocalcium phosphate (**MCP**) and monosodium phosphate (**MSP**) that were produced from either volcanic rock deposits or non-volcanic rock deposits were procured. Four synthetic diets based on cornstarch and potato protein were formulated by including each source of phosphate as the sole source of P in a diet. A P-free diet that was used to estimate the endogenous P loss from the pigs was also formulated. Forty pigs (BW: 15.6 ± 1.1 kg) were allotted to the 5 diets with 8 pigs per diet. Pigs were housed individually in metabolism crates that were equipped with a feeder and a nipple drinker. Each crate had a screen floor installed under the slatted floor to allow for total collection of feces. Diets were fed for 10 d, with an adaptation period of 5 d prior to the collection period that lasted 4 d. During the experiment, feed was provided in 2 daily meals that were fed at 0800 and 1600 h. Results indicated that ATTD and STTD of P were not different between MCP from volcanic or non-volcanic sources (89.8% and 93.8% respectively) or MSP from volcanic or non-volcanic sources (98.8 and 97.0% respectively). Values for digestibility obtained in this study agreed with previous data for STTD of P in MCP and MSP. In conclusion, differences in the STTD of P between volcanic and non-volcanic sources of MCP and MSP were not observed.

Key words: Phosphorus, feed phosphates, digestibility, volcanic

INTRODUCTION

Inorganic sources of P are usually added to diets for pigs to meet the requirement for digestible P (Jongbloed et al., 1991). The greater digestibility of P in feed phosphates compared with P in plant ingredients is the main reason for the use of inorganic P in diets for pigs (Kiarie and Nyachoti, 2010; NRC, 2012). To produce feed phosphate, it is necessary to mine phosphate rock, which can originate from either volcanic (igneous) deposits or non-volcanic (sedimentary) deposits. The mixed rock is crushed and treated with sulfuric acid to produce phosphoric acid (Gard, 2005; Leikam and Achorn, 2005; Stewart et al., 2005). To produce feed grade phosphates, phosphoric acid is used in a reaction with another mineral to produce phosphate salts, which are the main components of feed phosphates (Speight, 2017). Most feed phosphate used in swine nutrition are calcium phosphates such as monocalcium phosphate (**MCP**) and dicalcium phosphate (**DCP**). Calcium phosphates are produced by reacting phosphoric acid with calcium carbonate, but if phosphoric acid is reacted with sodium, monosodium phosphate (**MSP**) is produced (Gard, 2005). However, because of a number of possible impurities, there is variability in the concentration of P in phosphate rock from sedimentary deposits; whereas' rock phosphate from volcanic deposits usually contains less impurities and often has a greater concentration of P (Stewart et al., 2005).

Because of reduced concentrations of impurities, feed phosphates from volcanic deposits are believed to have a greater digestibility of P compared with those obtained from sedimentary deposits; however, this hypothesis has not been experimentally confirmed. Therefore, it was the

objective of this experiment to test the hypothesis that P in feed phosphate from volcanic sources have a greater digestibility when fed to growing pigs than feed phosphates from sedimentary deposits.

MATERIALS AND METHODS

The institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for the animal part of the experiment. Pigs used in the experiment were the offspring of L 359 boars mated to Camborough females (PIC, Hendersonville, TN).

Monocalcium phosphate and MSP that were produced from volcanic deposits were used. Both sources were obtained from YARA, Oslo, Norway. Monocalcium phosphate from non-volcanic rock deposits from Global Feed, Huelva, Spain, and MSP from non-volcanic deposits from ICL Performance Products, St. Louis, Mo, USA, were also used (Table 4.1).

Five synthetic diets based primarily on cornstarch and potato protein concentrate were formulated. Four diets each contained one of the feed phosphates from volcanic or non-volcanic sources as the only source of P (Tables 4.2 and 4.3). The last diet was a P-free diet that was used to estimate the basal endogenous loss of P from the gastrointestinal tract of the pigs. Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012). Feed consumption was limited to 3.2 times the energy requirement for maintenance (i.e., 197 kcal of ME per kg of $BW^{.60}$; NRC, 2012), and all diets were fed in meal form. Feed was provided each day in 2 equal meals that were fed at 0800 and 1600 h. Throughout the experiment, pigs had free access to water.

A total of 40 pigs [initial body weight (**BW**): 15.6 ± 1.1 kg] were randomly allotted to the 5 diets with 8 replicate pigs per diet. Pigs were placed in metabolism crates that had a feeder, a drinking nipple, and a slatted floor. After a 5-d adaptation period to the diets, a screen floor was installed below the slatted floor to allow for total collection of feces from each pig during a 4-d period, following standard procedures using the marker-to-marker approach (Adeola, 2001). Fecal samples were stored at -20 °C after collection.

Fecal samples were thawed and mixed within pig and diet, and then dried in a 50 °C forced air drying oven before analysis. Fecal, ingredient, and diet samples were analyzed for total P and Ca (Method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation (Method 975.03 B(b); AOAC, 2007). Diets were analyzed for N using the combustion procedure (method 990.03; AOAC, 2007) and crude protein (**CP**) was calculated as N × 6.25. Diets and ingredient samples were also analyzed for dry matter (**DM**) (Method 930.15; AOAC, 2007) and ash (Method 942.05; AOAC, 2007). Gross energy (**GE**) was determined using an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL).

The apparent total tract digestibility (**ATTD**) in the 4 feed phosphates was calculated according to the following equation (Almeida and Stein, 2010):

$$\text{ATTD (\%)} = \left(\frac{\text{Pi - Pf}}{\text{Pi}} \right) \times 100$$

where ATTD is the apparent total tract digestibility and Pi and Pf are the total P intake (g) and total output (g), respectively.

The basal endogenous P loss was determined from pigs fed the P-free diet according to the following equation (Almeida and Stein, 2010):

$$\text{Endogenous P loss(mg /kg of DMI)} = \left[\left(\frac{\text{Pf}}{\text{Fi}} \right) \times 1{,}000 \times 1{,}000 \right]$$

where Fi is the total feed intake (g of DM) from d 6 to 10. The daily endogenous P loss in pigs fed P-containing diets was calculated by multiplying the calculated endogenous P loss per kilogram of DMI by the DMI of each pig.

The standardized total tract digestibility (**STTD**) of P in the 4 feed phosphates was calculated using the following equation (Almeida and Stein, 2010):

$$\text{STTD (\%)} = \left[\text{Pi} - \frac{\text{Pf - Endogenous P loss}}{\text{Pi}} \right] \times 100$$

Normality of residuals was tested using the UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC). Data were analyzed using the PROC MIXED of SAS with the experimental unit being the pig. The model included the fixed effect of source of phosphate (i.e., volcanic vs. non-volcanic), feed phosphate (i.e., MCP and MSP), and the interaction between source of phosphate and feed phosphate. Treatment means were calculated using the LSMEANS statement and means were separated using the PDIFF with the Tukey adjustment option in SAS. Statistical significance and tendency were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively.

RESULTS AND DISCUSSION

Apatites mined from volcanic deposits contain fluorapatite [$Ca_{10}(PO_4)_6F_2$] and hydroxyapatite [$Ca_{10}(PO_4)_6OH$], whereas sedimentary deposits contain varieties called francolites [$Ca_{10-x-y}Na_xMg_y(PO_4)_{6-z}(CO_3)_zF_2F_{0.4z}$]. The degree of substitution of carbonate (CO_3)

for phosphate (PO_4) in francolite will determine the grade of P obtained. Varieties of francolite with low carbonate substitution may have a P concentration similar to apatites from volcanic deposits (Stewart et al., 2005).

The concentration of P and Ca in non-volcanic sources of P were greater compared with volcanic sources of P. Although these results were not expected, it is possible that phosphate rock composed of francolites with a low degree of substitution of calcium carbonate was used in manufacturing the non-volcanic feed phosphates. The concentrations of P and Ca in all feed phosphates are greater than concentrations reported previously (NRC, 2012; González-Vega et al., 2015; Kwon and Kim, 2017). This indicates that there likely were less impurities in the sources of MCP and MSP used in this experiment compared with that typically used in diets.

The interaction between source and the type of ingredient was not significant for feed intake, ATTD of P, and basal endogenous P loss. However, the interaction between source and type of ingredients on P intake, P output, and STTD of P was influenced by the type of ingredient.

No differences were observed for feed intake or the endogenous loss of P among the feed phosphates (Table 4.4). The basal endogenous loss of P obtained in this experiment (267 mg/kg DM intake) is slightly above the range reported from previous experiments (i.e., 139 to 226 mg/kg of DM intake; Petersen and Stein, 2006; Stein et al., 2006; Almeida and Stein, 2010; Kwon and Kim, 2017).

The intake of P from the diet containing MSP from the volcanic source was less ($P < 0.05$) than the intake of P from the diet containing MSP from the non-volcanic source. This difference may be attributed to the greater P concentration in the MSP from the non-volcanic

source. No difference between MCP from the volcanic source and MCP from the non-volcanic source was observed for P intake. However, no effect of the source was observed for intake of P.

For P output, ATTD of P, and STTD of P, no effect of source was observed. This indicates that regardless of the differences in P concentration, the P in all feed phosphates was digested with the same efficiency. The values for ATTD of P in MCP obtained in this experiment were 84.43% and 87.55% for the volcanic source and the non-volcanic source respectively. These values are within the range of values previously reported (Petersen and Stein, 2006; NRC, 2012; Kwon and Kim, 2017). In the case of MSP, both sources had an ATTD of P of 92%, which is in agreement with reported values (Petersen and Stein, 2006; NRC, 2012; Kwon and Kim, 2017).

The STTD of P in MCP has been reported in the range of 88.3% to 93.0% and for MSP, values from 93.8% to 98.2% have been reported (Petersen and Stein, 2006; NRC, 2012; Kwon and Kim, 2017). In the present experiment, values for STTD of P in the volcanic source and the non-volcanic source of MCP were 89.91% and 93.85%, respectively, and these values were not different. For MSP, the values for STTD of P obtained in this study were 98.8% and 97.0% for the volcanic source and the non-volcanic source, respectively. However, the ATTD and the STTD of P in the non-volcanic source of MSP were greater ($P < 0.05$) than the ATTD and STTD of P in MCP from volcanic sources.

No differences in Ca output or ATTD of Ca were observed among diets (Table 4.5). However, the intake of Ca in the diet containing MSP from the volcanic source was greater ($P < 0.05$) than Ca intake from the other diets. The ATTD of Ca that was calculated represents the ATTD of Ca for the mixture of MCP and limestone, however, for the 2 MSP diets, the ATTD of Ca represents the ATTD of Ca in limestone because MSP did not contribute Ca to the diets. The

ATTD of Ca in the 2 MSP diets is slightly lower than previous values (Lee et al., 2019; McGhee and Stein, 2019), but in agreement with results published by González-Vega et al. (2015) for ATTD of Ca in limestone. This indicates that the calculated ATTD of Ca of the limestone as the sole source of Ca in the MSP diets is within the range of reported data. The observation that the ATTD of Ca in the 2 MCP diets was not greater than in the 2 MSP diets indicates that the ATTD of Ca in the MCP used in this experiment is not greater than the ATTD of Ca in limestone. This observation contradicts observations by González-Vega et al. (2015) who observed greater ATTD of Ca in MCP than in calcium carbonate. However, it is possible that differences among processing procedures for MCP results in differences in ATTD of Ca.

CONCLUSIONS

The ATTD and STTD of P was not affected by the source of the feed phosphates used in this experiment and the hypothesis that MCP and MSP from volcanic rock has greater digestibility of P than MCP and MSP from other sources was rejected. The process of production of feed phosphates has been designed to meet a minimum concentration of P regardless of the quality of the phosphate rock used in manufacturing, but the concentration of P in the non-volcanic sources of MCP and MSP used in this experiment was greater than in the volcanic source. The ATTD of Ca for limestone obtained in this experiment is within the range of reported values.

TABLES

Table 4.1. Dry matter, ash, Ca, and P concentration in volcanic and non-volcanic sources of P[1]

	Volcanic sources		Non-volcanic sources	
Item	MCP	MSP	MCP	MSP
DM, %	93.57	97.43	93.67	99.60
Ash, %	75.59	84.55	73.36	90.92
Ca, %	16.60	1.01	18.15	0.27
P, %	22.99	23.96	24.07	29.02

[1]MCP = monocalcium phosphate, MSP = monosodium phosphate.

Table 4.2. Ingredient composition of experimental diets containing volcanic or non-volcanic sources of P[1]

	Volcanic sources		Non-volcanic sources		
Item, %	MCP	MSP	MCP	MSP	P-Free
Cornstarch	50.28	49.69	50.23	49.72	51.16
Potato protein concentrate	18.00	18.00	18.00	18.00	18.00
Sucrose	18.00	18.00	18.00	18.00	18.00
Solka floc[2]	4.00	4.00	4.00	4.00	4.00
Soybean oil	5.00	5.00	5.00	5.00	5.00
Limestone	1.18	1.92	1.10	1.92	1.92
Potassium carbonate	0.40	0.40	0.40	0.40	0.40
Vitamin-micromineral premix[3]	0.15	0.15	0.15	0.15	0.15
Volcanic MCP	1.62	-	-	-	-
Non-volcanic MSP	-	1.47	-	-	-
Volcanic MCP	-	-	1.75	-	-
Non- volcanic MSP	-	-	-	1.44	-
Magnesium oxide	0.10	0.10	0.10	0.10	0.10
Salt	0.40	0.40	0.40	0.40	0.40

Table 4.2. (Cont.)

His	0.15	0.15	0.15	0.15	0.15
L-Lys	0.35	0.35	0.35	0.35	0.35
DL- Met	0.27	0.27	0.27	0.27	0.27
L- Trp	0.05	0.05	0.05	0.05	0.05
L- Thr	0.05	0.05	0.05	0.05	0.05
Total	100	100	100	100	100

[1]MCP = monocalcium phosphate; MSP = monosodium phosphate.

[2]Fiber Sales and Development Corp., Urbana, OH.

[3] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30mg as sodium selenite and selenium yeast; and Zn, 125.1mg as zinc hydroxychloride.

Table 4.3. Nutrient composition of experimental diets containing volcanic or non-volcanic sources of P[1]

	Volcanic sources		Non-volcanic sources		
Item	MCP	MSP	MCP	MSP	P-Free
Gross energy, kcal/kg	4,234	4,126	4,200	4,235	4,159
Crude protein, %	15.85	15.66	14.98	15.17	15.97
Dry matter, %	94.95	94.78	94.82	94.75	94.93
Ash, %	2.56	3.23	2.72	3.55	2.63
Calcium, %	0.78	0.99	0.75	0.73	0.75
Phosphorus, %	0.47	0.37	0.40	0.51	0.03

[1]MCP = monocalcium phosphate, MSP = monosodium phosphate.

Table 4.4. Digestibility of P in volcanic and non-volcanic sources of P[1]

	Volcanic sources		Non-volcanic sources			
Item	MCP	MSP	MCP	MSP	SEM	P-value
Feed intake, g/d	602	649	620	632	33.66	0.791
P intake, g/d	2.84[ab]	2.43[b]	2.49[b]	3.20[a]	0.15	0.003
Fecal P output, g/d	0.45[a]	0.20[b]	0.31[ab]	0.25[b]	0.04	<0.001
ATTD[2], %	84.43[b]	92.00[a]	87.55[ab]	92.00[a]	1.28	<0.001
EPL[2], g/d	0.15	0.16	0.16	0.16	0.01	0.803
STTD[2], %	89.81[b]	98.77[a]	93.85[ab]	97.00[a]	1.28	<0.001

[a-b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]MCP = monocalcium phosphate; MSP= monosodium phosphate.

[2]ATTD = apparent total tract digestibility of P; EPL = endogenous P loss. The daily EPL was calculated by multiplying DMI by 267 mg/kg DMI; STTD = standardized total tract digestibility of P.

Table 4.5. Digestibility of Ca in diets containing volcanic and non-volcanic sources of P[1]

	Volcanic sources		Non-volcanic sources			
Item	MCP	MSP	MCP	MSP	SEM	P-value
Ca intake, g/d	4.70[b]	6.43[a]	4.65[b]	4.61[b]	0.28	<0.001
Fecal Ca output, g/d	2.46	2.20	1.85	2.05	0.41	0.754
ATTD, %	52.17	62.09	60.07	64.92	6.03	0.507

[a-b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]MCP = monocalcium phosphate; MSP= monosodium phosphate; ATTD = apparent total tract digestibility of Ca.

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CHAPTER 5: EFFECT OF MICROBIAL PHYTASE ON STANDARDIZED TOTAL TRACT DIGESTIBILITY OF PHOSPHORUS IN FEED PHOSPHATES BY GROWING PIGS

ABSTRACT

An experiment was conducted to test the hypothesis that the apparent total tract digestibility (**ATTD**) and the standardized total tract digestibility (**STTD**) of P in feed phosphates are increased by microbial phytase when fed to growing pigs. Sources of monocalcium phosphate (**MCP**), monosodium phosphate (**MSP**), and magnesium phosphate (**MgP**) from volcanic (igneous) deposits were procured for the experiment. Three corn-soybean based diets that contained 0, 500, or 4,000 units of microbial phytase (**FTU**) per kg, but no feed phosphates, were included. Nine additional diets were formulated by adding each of the 3 feed phosphates to the 3 basal diets. A P-free diet was also formulated to estimate the basal endogenous loss of P from pigs. Therefore, a total of 13 diets were used. A total of 117 pigs (BW: 15.56 ± 1.68 kg) were allotted to the 13 diets with 9 pigs per diet. Pigs were housed individually in metabolism crates equipped with a feeder and a nipple drinker. Installation of a screen floor under the slatted floor allowed for collection of feces. Diets were fed for 10 d, with the initial 5 d being a period of adaptation to the diet followed by a collection period of 4 d. During the experiment, pigs were fed equal amounts of feed twice daily at 0800 and 1600 h. Results indicated that for ATTD and STTD of P in all diets increased with the inclusion of 500 or 4,000 FTU per kg, but the ATTD and STTD of P in the feed phosphates were not affected by the inclusion of phytase. This indicates that the increase in ATTD and STTD of P that was observed in the mixed diets likely

was due to the release of P from phytate in corn and soybean meal and not from an increase in digestibility of P in feed phosphates. However, MgP had a lower ($P < 0.05$) ATTD and STTD of P than MCP and MSP. In conclusion, microbial phytase does not increase the digestibility of P in MCP or MSP, but the digestibility of P in MgP is less than in MCP or MSP.

Key words: digestibility, feed phosphates, phosphorus, phytase, pigs

INTRODUCTION

Phosphorus is the second most abundant mineral in the body of pigs (Cromwell, 2005). However, the digestibility of P in plant ingredients traditionally used in diet formulation is low (NRC, 2012). Therefore, feed phosphates are included in the diets to meet the requirement for P (Kiarie and Nyachoti, 2010). Feed phosphate production starts with phosphate rock that is treated with sulfuric acid resulting in phosphoric acid. Phosphoric acid is then used to produce feed phosphates via reaction with another source of minerals (i.e., calcium carbonate to produce dicalcium phosphate; Birky, 2017). Phosphate rock may be produced from volcanic (igneous) deposits or from non-volcanic (sedimentary) sources (Van Kauwenbergh, 2010). Feed phosphates produced from volcanic sources that are currently marketed include monocalcium phosphate (**MCP**), monosodium phosphate (**MSP**), and magnesium phosphate (**MgP**).

The low digestibility of P in plant feed ingredients, which is primarily due to the presence of phytate and salts of phytate in feed ingredients, may be ameliorated by addition of exogenous enzymes that can degrade the ester bonds between P and inositol in phytate (NRC, 2012). Phytate is present in the highest proportion as myo-inositol heakis-phosphate (**IP_6**) in most plant feed ingredients, with low quantities of IP_5 and IP_4 esters (Morales et al., 2016). Phytate is stable

at a wide pH range (Morales et al., 2016), which allows formation of complexes with different minerals under physiological conditions, such as Zn, Cu, Mn, Ca, and Fe (González-Vega et al., 2015a; Morales et al., 2016). Phytate from plant feed ingredients may, therefore, bind Ca from calcium carbonate in the intestinal tract, but because phytase can prevent the formation of Ca complexes, it may increase the digestibility of Ca in calcium carbonate (González-Vega et al., 2015b; Walk, 2016; Lee et al., 2019). However, there is no information about possible effects of phytase on the digestibility of P in feed phosphates. Feed phosphates do not contain phytate, but theoretically it is possible that phytate from plant ingredients in the diets may form complexes with P from feed phosphates in the gastrointestinal tract. If that is the case then it is expected that phytase will increase the digestibility of P in feed phosphates, but this hypothesis has not been tested. Therefore, the objective of this experiment was to test the hypothesis that microbial phytase increases the standardized total tract digestibility (**STTD**) of P in feed phosphates fed to growing pigs.

MATERIALS AND METHODS

The institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for the animal part of the experiment. Pigs used in the experiment were the offspring of L 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA).

Three corn-soybean meal based diets were formulated to contain 0, 500, or 4,000 units of microbial phytase (**FTU**; *Escherichia coli*; Quatum blue, Marlborough, UK). No feed phosphates were included in these diets. Nine additional diets were formulated by adding MCP, MSP, or

MgP to each of the 3 basal diets in quantities needed to bring the total concentration of P in the diets to the requirement for pigs. A P-free diet that was used to estimate the basal endogenous loss of P from pigs was also included in the experiment. In total, 13 diets were formulated (Table 5.1). Vitamins and minerals except Ca and P were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

A total of 117 pigs [initial body weight (**BW**): 15.6 ± 1.7 kg] were divided into 3 blocks with 39 pigs per block. Within each block, the 39 pigs were randomly allotted to the 13 diets with 3 replicate pigs per diet. Therefore, for the 3 blocks, there were 9 replicate pigs per diet. Pigs were placed in metabolism crates that had a feeder, a drinking nipple, and a fully slatted floor. After the 5-d adaptation period to diets, a screen floor was installed below the slatted floor to allow for total collection of feces from each pig during a 4-d collection period following standard procedures for the marker-to-marker approach (Adeola, 2001). Fecal samples were stored at -20 °C immediately after collection.

Daily feed provisions were equivalent to 3.2 times the energy requirement for maintenance (i.e., 197 kcal of ME × $BW^{0.60}$; NRC, 2012), which was provided in 2 equal meals that were fed at 0800 and 1600 h. Throughout the experiment, pigs had *ad libitum* access to water. Feed consumption was recorded daily and feed was provided in meal form.

At the conclusion of the experiment, fecal samples were thawed and dried in a 50 °C forced air-drying oven before analysis. Fecal samples, corn, soybean meal (**SBM)**, feed phosphates, and diet samples were analyzed for total P and Ca (Method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation [method 975.03 B(b); AOAC, 2007] and all diets and samples of corn, SBM, and feed phosphate were analyzed for dry matter (**DM**; Method

930.15; AOAC, 2007). Diet, corn, and SBM samples were also analyzed for N using the combustion procedure (method 990.03; AOAC, 2007) and crude protein (**CP**) was calculated as N × 6.25. Gross energy (**GE**) was analyzed in diet, corn, and SBM samples, using an isoperibol bomb calorimeter (Model 6400, Parr instruments, Moline, IL). Ash was analyzed in feed phosphates, corn, SBM, and diet samples (Method 942.05; AOAC, 2007), and diets were also analyzed for phytase (Method 2000.12; AOAC, 2007). Corn and SBM were also analyzed for phytic acid (Ellis et al., 1977).

The apparent total tract digestibility (**ATTD)** of P in the 12 P-containing diets was calculated according to the following equation (Almeida and Stein, 2010):

$$\text{ATTD (\%)} = \left(\frac{Pi - Pf}{Pi}\right) \times 100$$

where ATTD is the apparent total tract digestibility, and Pi and Pf are the total P intake (g) and total P output (g), respectively.

The basal endogenous P loss was calculated from pigs fed the P-free diet according to the following equation (Almeida and Stein, 2010):

$$\text{Endogenous P loss (mg/kg DMI)} = \left[\left(\frac{Pf}{Fi}\right) x\ 1{,}000\ x\ 1{,}000\right]$$

where Fi is the total feed intake (grams of DM) from d 6 to 10, (**DMI**) is the daily dry matter intake. The daily endogenous P loss in pigs fed P-containing diets was calculated by multiplying the calculated endogenous P loss per kilogram of DMI by the DMI of each pig.

The STTD of P in the 12 P-containing diets was calculated using the following equation (Almeida and Stein, 2010):

$$\text{STTD of P (\%)} = \left[\frac{\text{Pi - (Pf - daily endogenous P loss)}}{\text{Pi}} \right] \times 100$$

The concentration of STTD P in the ingredients was calculated by multiplying the amount of P in the ingredient by the STTD of P. The concentration of ATTD and STTD of P and STTD P in the 3 feed phosphates were calculated using the difference procedure (Adeola, 2001).

Normality of the residuals was tested using the UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC, USA). Data for the ATTD and STTD of P in the 12 P-containing diets were analyzed using PROC MIXED of SAS (SAS Inst. Inc., Cary, NC, USA) with the experimental unit being the pig. Least squares means were calculated for each independent variable using the LSMeans statement in SAS (SAS Inst. Inc., Cary, NC, USA). The statistical model included the level of phytase and the P source as the fixed effects and the random effects of period and replicate within period. Mean separation was conducted by the PDIFF option with the Tukey's adjustment if an effect was significant. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

RESULTS

Concentrations of P and Ca in ingredients and diets were in agreement with formulated values (Tables 5.2 and 5.3). Diets formulated to not contain exogenous phytase, analyzed <70 FTU per kg with the exception of the MSP diet that contained 98 FTU per kg. Diets formulated to contain 500 FTU analyzed between 360 and 540 FTU per kg, and diets formulated to contain 4,000 FTU per kg, analyzed between 3,200 and 3,700 FTU per kg.

There was no interaction between P source and inclusion of phytase for ADFI, P in feces, and endogenous P loss (Table 5.4). Pigs fed the basal diet without phytase had the lowest ($P <$

0.05) intake of P, and also the lowest (P < 0.05) ATTD of P and STTD of P, followed by the basal diets with inclusion of 500 or 4,000 FTU per kg. Pigs fed diets with 4,000 FTU per kg had the lowest ($P < 0.05$) concentrations of P in feces and the greatest ($P < 0.05$) ATTD and STTD of P compared with diets with 0 or 500 FTU per kg. No effect of inclusion of phytase was observed for ADFI and daily endogenous P loss. Pigs fed basal diets had the least ($P < 0.05$) ADFI, P intake, ATTD of P, endogenous P loss, and STTD of P, with no difference among the 3 sources of inorganic P. Pigs fed basal diets also had the least ($P < 0.05$) excretion of P in feces; whereas, pigs fed diets containing MgP had the greatest ($P < 0.05$) excretion of P in feces.

There was no effect of phytase inclusion on the ATTD or STTD of P among the 3 sources of P (Table 5.5). However, MgP had the least ($P < 0.05$) values for ATTD and STTD of P compared with MCP and MSP.

DISCUSSION

Concentrations of GE, DM, ash, Ca, and P in corn and SBM were in agreement with expected values (NRC, 2012), but the concentration of CP in corn was lower than expected (NRC, 2012). The values for phytate and phytate bound P in corn were greater than reported in the literature (González-Vega et al., 2015a); whereas, the values for phytate and phytate bound P for SBM were in agreement with reported data (Lagos and Stein, 2017). Concentrations of P, P bound in phytate, and Ca in corn and SBM; and the concentrations of Ca in MCP were also in agreement with previous data (NRC, 2012; González-Vega et al., 2015b; Kwon and Kim, 2017). However, concentrations of P in MgP and MSP were lower than reported data, whereas the concentration of P in MCP was greater (Fishwick, 1978; NRC, 2012; González-Vega et al., 2015b; Kwon and Kim, 2017).

Based on molecular mass, analytical grade MCP, MSP, and MgP should have concentrations of P of 26.5, 25.8, and 28.4% respectively. The observation that all 3 sources contained less P than the calculated values indicates that impurities in the form of other minerals or unreacted calcium carbonate were present in the 3 phosphates (Baker, 1989; Lee, 2020). The process of production of MgP and the amount of impurities can influence the concentration of P (Baniel et al., 1965), which may be the reason for the low concentration of P in the MgP used in this study. Production of feed phosphates is designed to produce a safe product that can be used in nutrition, which will remove most of the impurities. However, feed phosphates have variable concentration of other minerals that can negatively affect the concentration of P (Baker, 1989; Lima et al., 1995; 1999; Souza et al., 2009). Some minerals, such as Na, Mg, Fe, and Al, can react with P and form complexes that can decrease the availability of P.

The basal endogenous P loss was measured at 308.5 mg/kg of dry matter intake. This value is within the range of values for the endogenous loss of P calculated by the regression procedure (Shen et al., 2002; Dilger and Adeola, 2006), but greater than values reported from experiments where the basal endogenous P loss was calculated by feeding a P-free diet (Petersen and Stein, 2006; Stein et al., 2006; Almeida and Stein, 2010; Kwon and Kim, 2017).

The increase in ATTD and STTD of P observed in this experiment as phytase was added to the diets is in agreement with previous data (Harper et al., 1997; Adeola et al., 2004; Almeida and Stein, 2010; Kerr et al., 2010). The observation that the STTD of P in diets containing 4,000 FTU per kg was greater than in diets containing 500 FTU per kg is also in agreement with reported data (Almeida and Stein, 2012; Mesina et al., 2018; She et al., 2018; Arredondo et al., 2019) and demonstrates that 500 FTU per kg is not sufficient to fully release all P from phytate in a corn-SBM diet. However, the differences observed in P intake, ATTD, and STTD of P are

likely the result of the interaction between source of phosphorus and phytase inclusion. The effect of phytase in basal diets was greater than in diets containing feed phosphates. This indicates that the observed differences within diets are due to the inclusion of phytase; whereas the differences between the basal diets and the diets that contain feed phosphates are the result of the inclusion of a highly digestible source of P.

Despite the observed phytase effect on P digestibility in the corn-SBM diets, there was no effect of phytase on STTD of P in MCP, MSP, or MgP, which is likely because there is no phytate in these ingredients. This observation indicated that the increase in STTD of P in the mixed diets was due to release of P from phytate in corn and SBM, and not from increased digestibility of P in feed phosphates. However, it has been demonstrated that the STTD of Ca in calcium carbonate is increased by phytase (González-Vega et al., 2015b; Lee et al., 2019), which is likely due to formation of complexes between Ca and phytate in the gastrointestinal tract. Results from this experiment indicate that P from MCP, DCP, or MgP does not get bound to phytate in the intestinal tract and, as a consequence, phytase did not increase ATTD or STTD of P in MCP, DCP, or MgP.

The values for STTD of P in MSP and MgP that were calculated in this experiment were slightly lower than reported in previous research (NRC, 2012; González-Vega et al., 2015b; Kwon and Kim, 2017); whereas, the value for STTD of P in MCP was greater than published data (NRC, 2012; González-Vega et al., 2015b; Kwon and Kim, 2017). However, ATTD and STTD of P may vary among sources of MCP due to different inclusion rates of DCP in feed phosphates sold as MCP (Petersen and Stein, 2006) and impurities may also result in reduced digestibility of some sources. Regardless, the present data indicate that STTD of P in MgP is less than in MCP and MSP. There are limited data for ATTD and STTD of P in MgP. This may be

due to the low use of this ingredient in swine diets; monocalcium phosphate and DCP are the P supplements most widely used in diets for pigs (Petersen et al., 2011). However, the relative bioavailability of Ca is reduced in calcium sources containing Mg (Ross et al., 1984), which is likely because Mg antagonizes Ca absorption. The present data indicate that Mg may also antagonize P absorption, which may explain the reduced STTD of P in MgP compared with MCP and MSP.

CONCLUSIONS

The ATTD and STTD of P in feed phosphates were not affected by the inclusion of phytase in the diets. Data also confirm that STTD of P in MCP and MSP is very high, and these P-sources are, therefore, excellent sources of P in diets for pigs. However, the STTD of P in MgP is less than in MCP and MSP.

TABLES

Table 5.1. Ingredient composition of experimental diets containing MCP, MSP, or MgP that were produced from volcanic rock phosphates[1]

Item, %	Control			MCP			MSP			MgP			P-free
Phytase, FTU[2] / kg:	0	500	4000	0	500	4000	0	500	4000	0	500	4000	-
Ground corn	66.69	61.69	61.69	66.09	61.09	61.09	65.63	60.63	60.63	64.79	59.79	59.79	-
Soybean meal	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	-
Cornstarch	-	-	-	-	-	-	-	-	-	-	-	-	51.16
Potato protein concentrate	-	-	-	-	-	-	-	-	-	-	-	-	18.00
Sucrose	-	-	-	-	-	-	-	-	-	-	-	-	18.00
Soybean oil	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Solka floc[3]	-	-	-	-	-	-	-	-	-	-	-	-	4.00

Table 5.1. (Cont.)

Potassium carbonate	-	-	-	-	-	-	-	-	-	-	-	-	0.40
Magnesium oxide	-	-	-	-	-	-	-	-	-	-	-	-	0.10
Limestone	1.69	1.69	1.69	1.17	1.17	1.17	1.69	1.69	1.69	1.69	1.69	1.69	1.92
MCP	-	-	-	1.12	1.12	1.12	-	-	-	-	-	-	-
MSP	-	-	-	-	-	-	1.05	1.05	1.05	-	-	-	-
MgP	-	-	-	-	-	-	-	-	-	1.89	1.89	1.89	-
Vitamin-mineral premix[4]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Phytase premix[5]	-	5.00	5.00	-	5.00	5.00	-	5.00	5.00	-	5.00	5.00	-
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[1]MCP = monocalcium phosphate; MSP = monosodium phosphate; MgP = magnesium phosphate.

[2]FTU = phytase units per kilogram complete diet.

[3]Fiber Sales and Development Corp., Urbana, OH, USA.

Table 5.1. (Cont.)

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[4] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin,6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30mg as sodium selenite and selenium yeast; and Zn, 125.1mg as zinc hydroxychloride.

[5]Phytase (Quantum blue 5G; AB Vista, Marlborough, UK) was include in a premix using corn as a carrier. Two premixes were formulated to provide 500 or 4,000 FTU per kg of diet. The phytase premix used to provide 500 FTU per kg contained 10 FTU per gram of premix, whereas the phytase premix used to provide 4,000 FTU per kg contained 80 FTU per gram of premix.

Table 5.2. Composition of ingredients[1]

Item	Ingredient				
	Corn	Soybean meal	MCP	MSP	MgP
Gross energy, kcal/kg	3,878	4,134	-	-	-
Dry matter, %	87.87	88.67	92.62	98.81	96.62
Ash, %	1.00	6.88	80.15	85.23	86.36
Crude protein, %	6.87	46.16	-	-	-
Calcium, %	<0.01	0.35	16.60	1.10	1.00
Phosphorus, %	0.30	0.61	22.99	23.70	14.80
Phytate, %	0.75	1.50	-	-	-
P in phytate, [2]%	0.21	0.42	-	-	-
Non-phytate P, [3]%	0.09	0.19	-	-	-

[1]MCP = monocalcium phosphate; MSP = monosodium phosphate; MgP = magnesium phosphate.

[2]P in phytate was calculated as 28.2% of phytate (Tran and Sauvant, 2004).

[3]Non-phytase P was calculated as the difference between total P and phytate-bound P.

Table 5.3. Analyzed nutrient composition of experimental diets[1,2]

Item	Control diets			MCP diets			MSP Diets			MgP diet			P-free
Phytase (FTU/kg)[3]:	0	500	4,000	0	500	4,000	0	500	4,000	0	500	4,000	diet
Gross energy, kcal/g	3,980	4,002	3,989	3,969	3,991	3,973	3,998	3,986	3,953	3,958	3,971	3,956	4,192
Crude protein, %	18.42	19.30	20.41	19.70	18.70	19.00	19.92	18.94	19.25	19.19	18.43	20.00	14.90
Dry matter, %	89.42	87.95	89.05	89.12	87.80	87.55	89.09	88.99	88.79	89.40	88.97	89.17	94.27
Ash, %	4.84	4.96	4.60	5.42	5.52	5.32	5.61	5.26	4.86	6.02	5.47	5.96	2.32
Calcium, %	0.73	0.69	0.82	0.81	0.66	0.79	0.87	0.83	0.69	0.87	0.68	0.86	0.87
Phosphorus, %	0.31	0.34	0.37	0.58	0.57	0.60	0.58	0.59	0.57	0.60	0.58	0.59	0.03
Phytase, FTU/kg	<70	420	3,600	<70	360	3,200	98	360	3,400	<70	540	3,700	-

[1]MCP = monocalcium phosphate; MSP = monosodium phosphate; MgP = magnesium phosphate.

[2]The formulated ME of the diets was 3,523 kcal/kg for control diets; 3,500 kcal/kg for MCP diets; 3,482 kcal/kg for MSP diets; 3,451 kcal/kg for MgP diets; and 3,833 kcal/kg for the P-free diet. All diets contained the following quantities of standardized ileal digestible AA: Arg, 0.56%; His, 0.42%; Ile, 0.63%; Leu, 1.23%, Lys, 1.23%; Met, 0.36%; Phe, 0.72%; Thr, 0.73%; Trp, 0.20%; Val, 0.78%.

[3]FTU = phytase units per kilogram complete diet.

Table 5.4. Apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of P in diets containing different sources of P and different inclusions of phytase[1, 2]

	ADFI, g/d	P intake, g/d	P in feces, g/d	ATTD of P, %	EPL[3, 4], mg/d	STTD of P, %
Basal diets						
0 FTU[5]	663.6	2.0[f]	1.3	36.2[g]	186.9	45.4[g]
500 FTU	689.0	2.4[e]	1.0	59.4[ef]	190.9	67.5[ef]
4,000 FTU	745.1	2.8[d]	0.5	81.2[a]	209.0	88.6[a]
MCP diets						
0 FTU	781.1	4.6[abc]	1.7	62.8[ef]	219.2	67.7[ef]
500 FTU	780.8	4.5[abc]	1.2	73.1[bc]	215.9	77.9[bc]
4,000 FTU	777.0	4.6[a]	0.8	82.5[a]	214.3	87.1[a]
MSP diets						

Table 5.4. (Cont.)

0 FTU	756.6	4.4^{bc}	1.5	65.2^{de}	212.3	70.1^{de}
500 FTU	781.8	4.6^{abc}	1.2	72.7^{bcd}	219.2	77.5^{bcd}
4,000 FTU	759.6	4.3^{c}	0.7	80.9^{a}	212.5	85.7^{a}
MgP diets						
0 FTU	768.5	4.6^{ab}	2.0	55.8^{f}	216.4	60.5^{f}
500 FTU	768.8	4.5^{abc}	1.5	66.7^{cde}	215.5	71.5^{cde}
4,000 FTU	765.8	4.5^{abc}	0.9	78.8^{ab}	215.1	83.6^{ab}
SEM	0.02	0.12	0.13	3.43	6.91	3.43
P-value						
P source	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Phytase	0.326	0.030	<0.001	<0.001	0.554	<0.001

Table 5.4. (Cont.)

P source × phytase	0.183	<0.001	0.814	<0.001	0.105	<0.001

[1]Data are means of 9 observations per treatment.

[2]MCP = monocalcium phosphate; MSP = monosodium phosphate; MgP = magnesium phosphate.

[3]EPL = endogenous phosphorus loss. The daily endogenous P loss (mg/d) for each diet was calculated by multiplying the endogenous P loss by the daily dry matter intake of each diet.

[4]The endogenous P loss was 308.5 mg/kg of dry matter intake.

[5]FTU = phytase units per kilogram complete diet.

Table 5.5. Apparent total tract digestibility (ATTD), standardized total tract digestibility (STTD) of P, and standardized total tract digestible (STTD) P in different sources of P at different inclusions of phytase[1,2]

	ATTD of P, %	STTD of P, %	STTD P, % in ingredient
MCP diets			
0 FTU[3]	94.40	94.01	21.55
500 FTU	89.43	89.78	20.58
4,000 FTU	84.74	85.18	19.53
MSP diets			
0 FTU	92.79	92.34	21.94
500 FTU	88.59	88.84	21.08
4,000 FTU	86.77	87.76	20.83
MgP diets			
0 FTU	78.15	77.85	11.50

Table 5.5. (Cont.)

500 FTU	79.90	80.53	11.81
4,000 FTU	74.50	75.57	11.16
SEM	5.63	5.62	1.16
P-value			
P source	<0.001	<0.001	<0.001
Phytase	0.151	0.277	0.239
P source × Phytase	0.900	0.875	0.850

[1]Data are means of 9 observations per treatment.

[2]MCP = monocalcium phosphate; MSP = monosodium phosphate; MgP = magnesium phosphate.

[3]FTU = phytase units per kilogram complete diet.

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CHAPTER 6: CONCLUSIONS

Results from this work indicated that the processes to produce feed phosphates are efficient to generate a product with a specific concentration of P to be delivered to the animal and with low concentrations of potentially harmful minerals, regardless of the variability in its concentrations among all sources. The lower concentration of potentially harmful minerals than the tolerance level of the animal allows the use of these ingredients in formulation of animal diets.

Feed phosphates can be produced from rock phosphate from volcanic and non-volcanic sources, and even though volcanic sources have theoretically less impurities, the apparent total tract digestibility (**ATTD**) and standardized total tract digestibility (**STTD**) of P was not different between the two sources of monocalcium phosphate (**MCP**) and monosodium phosphate (**MSP**). The inclusion of phytase did not affect the ATTD or STTD of P in MCP, MSP or magnesium phosphate (**MgP**); however, it was also observed that MgP had a lower ATTD and STTD of P than MCP and MSP. These feed phosphates have a very high digestibility of P and, therefore, are excellent sources of P to be used in diet formulation.