Featured Article

Phosphorus and nitrogen nutrition in swine production

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Implications

- Nitrogen and phosphorus are essential nutrients for all living organisms.
- Excesses are damaging to the environment, causing eutrophication and acidification.
- To optimize phosphorus and nitrogen use by pig, the intakes must be in accordance with the requirements, which require a precise system at all levels namely:
  1. A precise estimation of phosphorus and nitrogen values of feedstuffs.
  2. A precise estimation of phosphorus and nitrogen requirements.
  3. A system that allowed to distribute the feed the closest as possible to each animal requirements.

Key words: environment, nitrogen, nutrition, phosphorus, pig

Introduction

Livestock have become one of the fastest growing agricultural sectors in the world. Intensification has increased yields and efficiency while reducing costs. This is especially true for pork and chicken, which are the most consumed meats in the world. The global animal protein industry faces an unprecedented challenge as we enter the third decade of the 21st century. With more than 7 billion people currently living on the planet, population growth, and rising per capita income in low-income countries are expected to increase food demand by 48.6%, according to the FAO. Meeting future food demand means that these gains must continue to be made through improved genetics, nutrition and husbandry, and the adoption of performance-enhancing technologies (Capper, 2020). This, while minimizing the environmental impact of animal production including nitrogen (N) and phosphorus (P) excretion and greenhouse gas (GHG) emissions to reduce carbon footprint.

In this regard, agriculture is the source of approximately 30% of global GHG emissions and pork production represents about 5% of global agricultural GHG emissions, meaning less than 2% of total GHG, according to FAO inventories. Although pork and poultry production are among the animal proteins with the least impact on the environment, the widespread consumption of these meats means that their environmental impact must be considered. Their environmental impact primarily originates from the production of their feed ingredients that represent more than 50%. Losses of N and P lead to severe eutrophication problems in many regions of the world; livestock production systems generally have lower nutrient efficiency than crop systems.

Plants, animals, and humans cannot exist without P. As an essential element, it is crucial for food production. Worldwide production depends on rock phosphate, a nonrenewable resource. Therefore, a strong need exists for increased recycling and efficient use of P throughout the food production system. Besides, due to concentration of swine production in some regions (e.g., Brittany, Quebec, USA Midwest region, The Netherlands) and the high amount of liquid manure that are costly to transport, P accumulates in the soil and the risk of P discharge into water bodies and eutrophication is high. Improved P management practices are necessary to prevent eutrophication of water bodies due to P surpluses, avoid P deficits to preserve soil fertility in the long term, safeguard the mineral P reserves and thereby minimize phosphate rock import dependency. Nitrogen is a main component of living beings. In contrast to P, there is no N scarcity as N_2 constitutes 80% of the atmosphere. The production of mineral and synthetic fertilizers, especially nitrogen, uses large amounts of fossil fuel energy, and thus produces a lot of GHG. Moreover, excess N excreted by animals is an issue, as over a third of N applied to field, including in manure form, is lost in NH_3, nitrate, or N_2O emissions. They respectively cause acidification, eutrophication, and climate change. As for P, this is even more an issue in regions with concentrated pig production. Optimization of N nutrition and fertilization practices is necessary to reduce N losses and their environmental impacts, as well as the demand for energy-intensive mineral fertilizers. These environmental challenges are also more and more relevant for competitiveness given the postpandemic economic recovery hampering supply

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chains and the war in Ukraine that have caused the prices of raw materials and inputs (N and P) costs for feedstuffs to rise by 50% to 100%.

There is a clear and pressing need to better manage our planet's resources. The natural cycle of many nutrients but especially P has been perturbed leading to the point that we must reconcile the decreased supply of phosphate rock as a resource, and the overabundance of phosphate and nitrogen in water systems leading to eutrophication. This article will provide an overview of where we are in terms of optimizing the use of N and P by pigs and future research areas.

Nitrogen and Phosphorus in Swine Nutrition

Fate of ingested nitrogen and phosphorus

Nitrogen and P are required for pig maintenance and growth. Pigs do not require or use nitrogen directly but amino acids (AA) that contain nitrogen. They can directly use P in the form of orthophosphates. All nutrients ingested cannot be used by animals and thus, it is first important to understand and represent accurately the bioavailability of AA and P which is defined as the proportion of ingested dietary AA and P that is absorbed in a chemical form that renders them potentially suitable for metabolism or body deposition. Bioavailability is difficult to measure and has many drawbacks that have led to the development of another methodology, the digestibility. This method reflects enzymatic hydrolysis, solubilization, and microbial fermentation of ingested P and proteins and peptides and absorption of AA, peptides, and phosphate from the gastrointestinal lumen. Proteins are cleaved by enzymes produced by the stomach and pancreas in the proximal small intestine and absorbed in the small intestine, mainly in the jejunum. Free AA do not need to be hydrolyzed and are absorbed in the duodenum. Undigested protein reaches the hindgut, where fermentation of AA takes place, modifying the composition of digestive content. Thus, to accurately measure nutrients absorbed by pigs, digestibility is determined at the ileal level for AA using pigs with an ileal canula or an ileo-rectal anastomosis to by-pass microbial fermentation in the hindgut (NRC, 2012). Fecal level is preferred for P, because the digestibility values are the same as the ileal levels, but it is less difficult and expensive to evaluate (NRC, 2012; Figure 1). The AA and phosphorus absorbed by animals come from ingested feed but also from endogenous secretions into the digestive tract. Digestibility is therefore expressed as apparent (AID, apparent ileal digestibility; ATTD, apparent total tract digestibility; Table 1) or standardized (SID or STTD). In the standardized system, the basal endogenous losses, which represent the minimal loss of a nutrient, independent of feed composition but influenced by dry matter intake are evaluated and considered in the digestibility estimation (Stein et al., 2007). These losses are now measured by measuring the fecal phosphorus or AA content of pigs fed with phosphorus or protein-free diets (NRC,2012). The SID and STTD systems are preferred because AID and ATTD are affected by dietary level of AA and phosphorus inducing a lack of additivity of feedstuff values (NRC, 2012). Also, it is worth noting that endogenous losses are not negligible especially for nitrogen (1% of phosphorus intake vs. 4% of nitrogen intake) and impact differently different AA: 3% of Lysine, 2% of Methionine, and 5% of Tryptophane and valine for 50 kg pigs (Sauvant et al., 2004).

Feed formulation

In swine nutrition, mathematical optimization techniques, linear programming, have been used for many decades for least cost formulation. Optimization algorithms determine the relative quantities of ingredients that constitute an optimal diet, with respect to nutritional requirement and a set of other model constraints such as maximum and minimum incorporation rate at the least cost as possible. In recent and future years, the focus of diet optimization studies shifted from cost only to environmental footprint considerations given the

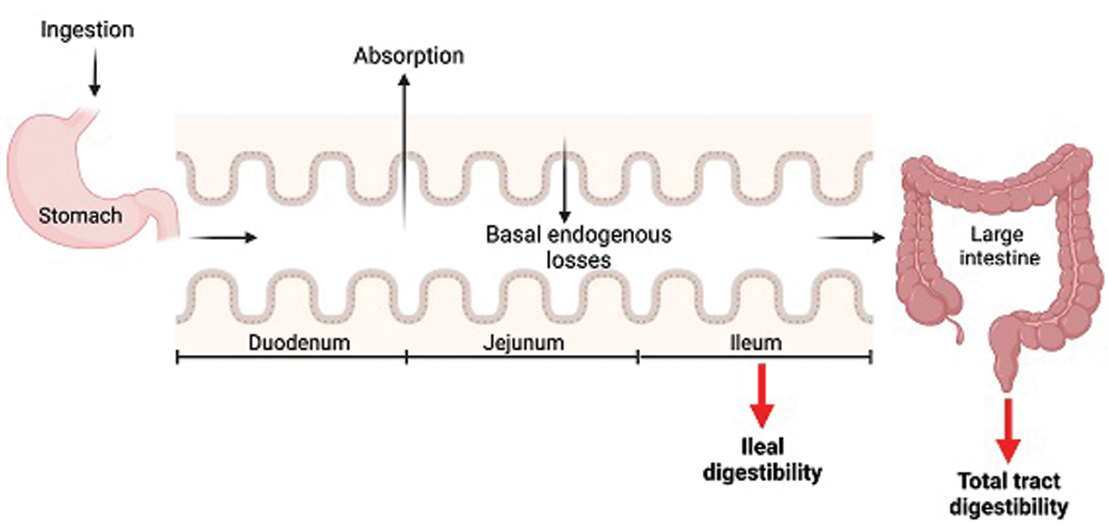


Figure 1. Fate of ingested nitrogen and phosphorus in the gastrointestinal tract.

Table 1. Ileal and total tract digestibility equations

Items	Equations
Apparent total tract digestibility phosphorus, %	$[(Phosphorus_{intake} - Phosphorus_{fecal})/Phosphorus_{intake}] \times 100$
Standardized total tract digestibility phosphorus, %	$[(Phosphorus_{intake} - (Phosphorus_{fecal} - \text{Phosphorus basal endogenous losses}))/Phosphorus_{intake}] \times 100$
Apparent ileal digestibility AA, %	$[(AA_{intake} - AA_{ileum})/AA_{intake}] \times 100$
Standardized ileal digestibility AA, %	$[(AA_{intake} - (AA_{ileum} - \text{AA basal endogenous losses}))/AA_{intake}] \times 100$

pressing environmental challenges that society faces today, such as climate change and resource depletion. To reach this goal, 3 components need to be satisfied: 1) precise estimation of animal requirements, 2) precise estimation of ingredients value, and 3) provision to the animal in an efficient way which will be discussed in the following sections.

Precise Estimation of Animal Phosphorus and Nitrogen Requirements

General concepts

The phosphorus and AA requirements were first determined according to a global approach. It consists of measuring different performance criteria (growth rate, feed conversion ratio, etc.) in dose–response trials. If all the criteria are not satisfied simultaneously, the requirement is then considered to be the one that optimizes the most important criterion. This approach was progressively replaced by the factorial approach because it is more precise. In this approach, the requirements correspond to the addition of the requirements for each physiological function (e.g., for maintenance and growth in growing pigs). With the emergence of this method came the consideration of the intestinal absorption of phosphorus and AA. This approach led to the development of several models to determine the phosphorus and AA requirements (van Milgen et al., 2008; NRC, 2012; Bikker and Blok, 2017; Lautrou et al., 2020). The factorial modeling approach is based on body composition and a fixed efficiency of utilization of SID AA, estimated experimentally (Stein et al., 2007). Due to a fixed AA profile of gain, AA requirements profile is also considered constant for growing pigs and the ideal protein concept was introduced to model nitrogen metabolism. Lysine being the first limiting AA, all requirements are expressed as a ratio to SID lysine (Sève, 1994). Currently, model-based requirements cover all AA. Dose–response studies have been performed to understand the ratios relative to lysine for the limiting amino acids of threonine, tryptophan, methionine, valine, and isoleucine. Leucine, histidine, phenylalanine, and tyrosine have only been studied in piglets and more data is necessary for pigs, now that low crude protein diets are reaching limiting levels for these AA. Nowadays, only essential AAs are used to formulate pig diets but the existence of a nitrogen or nonessential AA requirement is questioned (NRC, 2012; Wu et al., 2013). Optimum ratio of essential AA to nonessential AA or nitrogen has been found in pigs (Heger et al., 1998; Lenis et al., 1999). More recently, indication of a strict nitrogen requirement has been shown by improved performance with urea–nitrogen supply (Mansilla et al., 2017).

Factors that modulate requirements

Due to variation in growth performance, nitrogen and phosphorus requirements are affected by pig bodyweight, sex, and genetic lines (NRC, 2012). Production context also affects requirements, such as health status (Kampman-Van De Hoek, 2015). Heat stress, which will become more and more of an issue, also impacts digestive performance and metabolism efficiency, impacting AA availability and requirements (Morales et al., 2020). Effect of both the amounts and forms of dietary AA and phosphorus (Letourneau-Montminy et al., 2012; Morales et al., 2020) and of nutrients interactions on utilization efficiency should be further explored to represent more accurately phosphorus and AA use by the pig. Among them, for N, there is strong interaction between AA such as valine, leucine, and isoleucine, the branched-chain amino acids required for protein synthesis but sharing the same enzymes for degradation with leucine that is generally in excess in swine diet (NRC, 2012). Recently, studies showed that leucine excess may increase the need for dietary valine and Ile in piglets (Cemin et al., 2019). For P, the interaction with calcium is well known and should be considered to optimize it's use (Létourneau-Montminy et al., 2012; NRC, 2012). Individual variability in requirements also exists due to variable potential and efficiency of animals (Pomar et al., 2015). These influencing factors and variability begin to question the use of the ideal protein for feed formulation.

Moreover, the requirements differ from one estimation model to another due to different objectives and assumptions. For example, for P, in INRAporc (van Milgen et al., 2008), the objectives are to maximize the bones growth, while it is to maximize the average daily gain in the NRC (2012).

Precise Estimation of Phosphorus and Nitrogen Value of Feedstuffs

Plant origin

Plant ingredients make up a major part of pig diets and are the main providers of nitrogen. Ingredients vary in terms of nitrogen content but also AA profile. Soybean meal is the most used nitrogen source as its AA profile is the closest to pig requirements. Due to their high inclusion in diets, cereals provide an important share of nitrogen to pigs. Type of cereal used is important to take into consideration as their AA profile varies widely. Coproducts are economically interesting, but a careful use is needed due to high variability of nutritional composition.

Around 50% to 80% of the phosphorus in all plant-based ingredients is present as phytic acid (Sauvant et al., 2004;

Selle and Ravindran, 2008; NRC, 2012) and more precisely in the form of salts, called phytates. These phytates are solubilized at gastric pH, but the higher pH of the small intestine promotes their reformation or *de novo* complexation, decreasing the minerals and trace elements absorption (Angel et al., 2002). Unless phytase is utilized, part of the phosphorus of vegetable origin is hardly absorbable by the pig. Phytates also form insoluble complexes with proteins, AA, and starch and thereby decrease the digestibility in the small intestine and utilization of these nutrients (Selle and Ravindran, 2008).

Animal origin

The demand for quality food protein is growing. Globally, about one-third to one-half of every animal raised for meat, milk, or eggs is not consumed by humans. Slaughterhouse by-products are recovered primarily by the rendering industry. They are processed into meat meal and meat bone meal (MBM) that can be distinguished by higher mineral content in phosphorus in the one containing bone. They have been thoroughly characterized and can offer stable composition throughout the same processing plant (NRC, 2012). However, in practice they are utilized only in poultry. Besides, although not available yet, it is well-documented that peptides may be generated from slaughterhouse by-products (liver, lung, heart, kidney, blood, etc.) from chicken, sheep, and cattle by hydrolysis, to serve as protein sources or bioactive or techno-functional supplements.

Synthetic and inorganic forms

To complement AA supplied by plants and animal sources, free AA produced by chemical synthesis or bacterial fermentation are used. They allow more flexibility in formulation and are required to produce feeds with an AA profile closer to animal requirements. Contrary to macro ingredients, free AA are 100% digestible as they don't rely on proteolysis (Kurz and Seifert, 2021). Currently, lysine, methionine, threonine, tryptophan, valine, isoleucine, leucine, and histidine are commercially available, meaning that phenylalanine is the only essential AA not on the market. However, use of newly available AA is not economically viable to use in pig diets.

The most used inorganic phosphorus forms are dicalcium phosphate, monocalcium, and monodicalcium phosphates. Magnesium, calcium–magnesium, ammonium, and sodium phosphates are also available for use in livestock feed. To limit the phosphorus excretion, the most digestible phosphates are preferred, although price also is considered. Monocalcium phosphate is more digestible than monodicalcium phosphate, which is more digestible than dicalcium phosphate and dicalcium phosphate dihydrate is more digestible than the anhydrous form (Sauvant et al., 2004). The phosphorus from inorganic source is highly digestible: around 78% of ATTD (Létourneau-Montminy et al., 2012).

Enzymes

Proteases are used to increase nitrogen digestibility. Their effect is not protein or AA specific, thus use is limited to improve nitrogen nutrition as they do not improve AA balance of diets. Furthermore, their effect is variable, not well quantified and increased digestibility of protein doesn't translate to improved feed efficiency (Torres-Pitarch et al., 2019). Phytases are enzymes that hydrolyze phytic acids of plant ingredients and release the phosphate groups and other nutrients that are linked such as AA (Zouaoui et al., 2018). Some plant raw materials have their own phytase activity. The level of this activity depends on the ingredient and the part used (NRC, 2012). Plant phytase is sensitive to heat (more than microbial phytases), since its activity is partially or completely inactivated after high temperature treatment (>70°C) such as those for pelleting (Selle and Ravindran, 2008). Exogenous phytase are also developed and continuously improved. These enzymes were isolated first from fungi (first generation), then new techniques allowed the production of phytases by bacteria and yeast, leading to the second generation of phytases. New phytases and generations of this enzyme are regularly released, demanding continuous evaluation of the potential release of the phosphorus and other nutrients by phytase to use them efficiently.

Factors that modulate feedstuff values

All the methods described earlier give a unique phosphorus or AA value for each feedstuff regardless of the interactions with other components of the diet (e.g., fiber, calcium) or with pig physiology. Concerning nitrogen, enzymatic activity increases with protein ingestion. Digestibility is also affected by fiber content which varies with the use of by-products or not. Form of nitrogen supply, i.e., use of free AA impacts expression of enzymes and transporters, affecting digestibility of protein-bound AA (Kurz and Seifert, 2021). Overall, variation of AA digestibility in practical diets is low enough that an additive model is adequate. For P, a mechanistic model of Létourneau-Montminy et al. (2011) predicts the effect of the most relevant physiological processes involved in phosphorus digestion and absorption. This model considers the phosphorus dietary forms, the effect of phytase, the dietary calcium but also the transit time and pH of the different gastrointestinal sections. In a similar approach, Strathe et al. (2008) have developed a mathematical model to study the kinetics of digestion and absorption in growing pigs. The major organic nutrients are considered: dietary protein, endogenous protein, amino acids, nonamino acid and nonprotein nitrogen, lipids, fatty acids, starch, sugars, and dietary fiber.

Provision of Phosphorus and Nitrogen to Pigs in an Efficient Way

Feeding systems available

Once animal requirements and feed composition are reliably known, feed must be supplied efficiently to maximize nutrient use by the animals. A first way of improving nutrient supply is to better follow the evolution of requirements with pig growth, compared to a single-diet growing–finishing phase. Phase feeding consists of increasing the number of phases to be closer to animal requirements and reduce nitrogen and phosphorus excretions caused by excess supply (Figure 2). Currently, six or more phases are often used for growing–finishing pigs. To maximize performance, feeds are formulated to cover the requirements of the midpoint of the weight range of the feeding phase. Thus, nitrogen and phosphorus are below the requirement for the most demanding animals at the beginning of the phase and above the requirement for those animals by the end of the phase (Menegat et al., 2020). Therefore, increasing the number of phases could reduce nitrogen and phosphorus excretions. Phase feeding can go as far as daily changes of diet and is then called multiphase feeding. Requirements of each pig group are re-evaluated daily, and the diet changed by mixing two extreme feeds (rich and poor in nutrients). Transition from two to four phases reduced respectively N and P excretion by 6% and 4%, transition to daily multiphase reduces them by 9 and 5 (Monteiro et al., 2016). This strategy can also reduce feed costs as it reduces the amount of feed with high nutriment concentration needed. It also lowers manure treatment costs linked to high concentration of N and P in slurry.

Finally, the better feeding system to reduce excess of nutrients in the diet, and thus excretion is the precision feeding system (Pomar et al., 2015). In this system, pigs are fed individually, and their diets change every day to be closer to their own requirements. In this way, individual variability is taken into consideration. This system requires specific equipment that is not currently available for commercial production and also robust algorithms to fit real-time individual requirement curves that have to be developed for each AA and phosphorus and calcium. Using modeling approach reduction of nitrogen and phosphorus excretion is high with precision feeding: 16% for nitrogen and 6% for phosphorus compared to multiphase feeding (Monteiro et al., 2016).

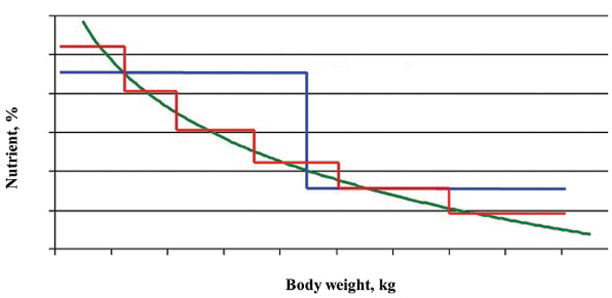


Figure 2. Phase feeding vs. daily requirements in amino acids and phosphorus.

Maximizing animal efficiency

Apart from a strategy to fulfill the more precisely as possible the requirement as previously described; it is possible to reduce phosphorus momentarily without affecting performance while reducing excretion. Since animals have a survival strategy to overcome some mineral deficiencies by enhancing digestion and increasing the efficiency of utilization of the deficient nutrient (Underwood and Mertz, 1987) a strategy named «Depletion-Repletion» has been developed (Lautrou et al., 2021). This strategy consists of reducing phosphorus and calcium input below the animal's requirements over some period of growth and then increasing the supply as needed. It induces an increase of phosphorus digestive efficiency and metabolic utilization and a decrease in phosphorus intake and excretion while maintaining growth and bone mineralization. Overall, the depletion–repletion strategy reduced dietary phosphate use and P release by about 40% (Lautrou et al., 2021).

Due to AA being limiting before N, diets can be optimized by reducing CP content and supplying an AA profile closer to ideal protein, thanks to free AA. This reduces AA supplied in excess that are catabolized and excreted in urine (Figure 3). With the increase availability of free AA, increased CP reduction is studied and applied in pig diets. Low crude protein diets correctly supplemented with free AA don't affect growth performance while reducing nitrogen excretion by 8% per %-point of crude protein reduction, and urinary nitrogen excretion by 10% per %-point (Cappelaere et al., 2021).

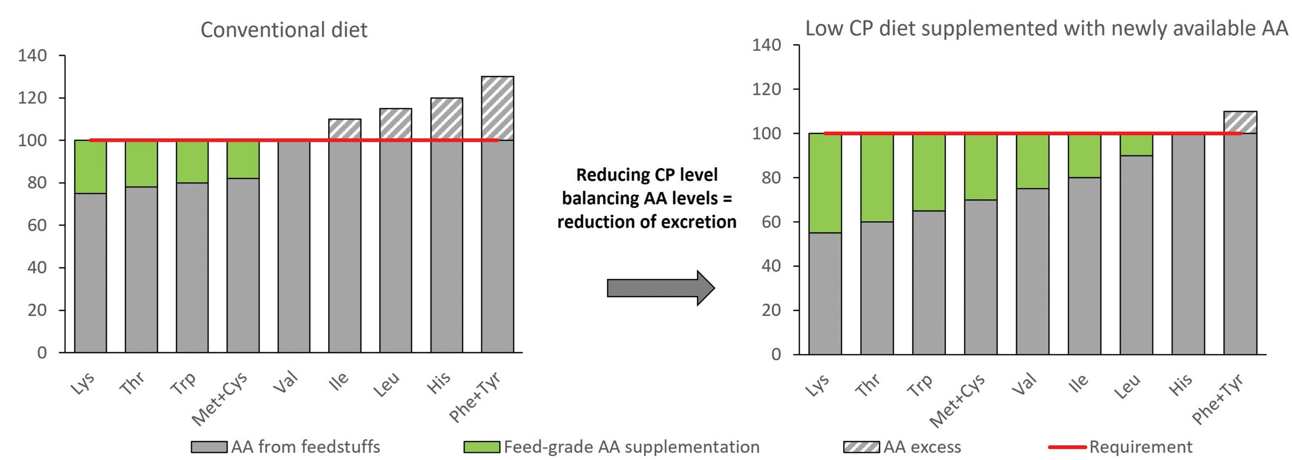
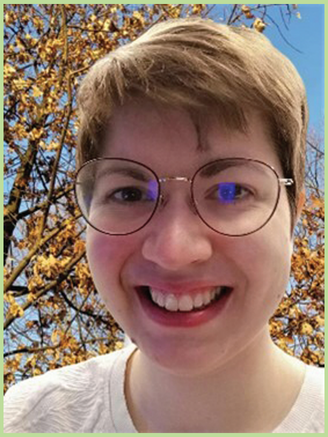


Figure 3. Principle of low crude protein diet supplemented with free amino acids strategy to reduce nitrogen excretion.

About the Authors



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Conclusions

Optimization of N and P nutrition is central to reducing the environmental impact of pig production. Robust nutrition systems are available to measure and express N and P requirements and feed supply allowing nutritionists to closely represent nutrients available for the pig. Thanks to this knowledge and available models, feed can be formulated and distributed efficiently to pigs, reducing nutrients supplied in excess. Low CP strategies, P depletion–repletion, multiphase feeding, or precision feeding can be combined for increasing efficiency of N and P use. To successfully implement those strategies, especially precision feeding, further research is needed to better understand and control the factors influencing AA and P digestion, absorption, and metabolic use such as dietary interactions, rearing context and conditions, genetic types, and intrinsic individual variability. Improving efficiency and reducing excesses at the animal level is important but to improve the sustainability of pig production, nutrient flows should be considered at the agricultural system level and strategies should take into account the impact of feed production and the effect on manure potential. Life cycle assessment is thus the indicated tool to correctly evaluate environmental benefits of N and P feeding strategies.

Conflict of interest statement. None declared.

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