Feed additives are compounds used in swine diets with the purpose of enhancing performance and health. Many non-antibiotic feed additives have been proposed or evaluated for improving growth performance, regulating gut microbiota, supporting immunity, ameliorating environmental challenges, and enhancing reproductive performance. However, the main challenge with non-antibiotic feed additives is the fact that many have not generated consistent effects or have not been economically justified. A brief overview of non-antibiotic feed additives available for inclusion in swine diets, the proposed mode of action, and the summary of effects on performance are provided in this fact sheet.

Acidifiers

Acidifiers are compounds classified as organic or inorganic acids. Organic acids include formic, fumaric, lactic, benzoic, propionic, and citric acids. Inorganic acids include hydrochloric, sulfuric, and phosphoric acids. Salts of acids also have been used as acidifiers, including calcium-formate, potassium-diformate, sodium-diformate, and sodium-fumarate. Blends of acidifiers are often commercially available because organic and inorganic acids may have a synergistic effect. In addition, some commercial acidifiers contain protected acids that are coated with fatty acids or other molecules, mainly to allow the release of the acid in a targeted location in the gut with the goal to improve effectiveness (Upadhaya et al., 2014).

The mode of action of dietary acidifiers has not been fully understood, but several mechanisms have been proposed. Acidifiers are believed to enhance growth performance via pH reduction in the digestive tract, which improves nutrient digestibility and promotes growth of beneficial bacterial while inhibiting pathogenic bacteria (Jacela et al., 2009a).

Acidifiers have been commonly targeted for weanling pigs. Organic acids have been shown to improve growth performance of weanling pigs more consistently than inorganic acids (Kil et al., 2011; Suiryanrayna and Ramana, 2015; Liu et al., 2018). However, inorganic acids have been often considered as an alternative to organic acids because of lower cost. Acidifiers may also benefit grow-finish pigs (Tung and Pettigrew, 2006), particularly under transition or stressful conditions. In sows, use of acidifiers in the diet improves nutrient digestibility and reduces urinary pH, which aids in controlling the incidence of urinary tract infections (Kluge et al., 2010).

The magnitude and consistency of the responses to acidifiers are variable depending on the nature of acids, inclusion rate, combination of acids, and diet composition (Jacela et al., 2009a). For most acidifiers, the inclusion of excessive levels in the diet affects palatability and decreases feed intake. Also, some acidifiers are corrosive and pose handling and equipment issues during feed manufacturing. Generally, inorganic acids are the most corrosive and salts of acids are the least corrosive acid forms.

Prebiotics

Prebiotics are non-digestible oligosaccharides that can selectively stimulate the growth of beneficial bacterial in the hindgut (Gibson and Roberfroid, 1995). To be considered a prebiotic, the oligosaccharides must be resistant to digestion and absorption, be fermented in the hindgut, and selectively stimulate the growth of non-pathogenic bacteria in the hindgut (Gibson et al., 2004). Bifidobacteria and lactobacilli growth is beneficial for gut health due to short chain fatty acids (SCFA) production. Short chain fatty acids reduce the pH, eliminate enteric pathogens, and also stimulate gut development and integrity. Essentially, prebiotics serve as substrates for fermentation and production of SCFA by beneficial bacteria.

The most common prebiotics are inulin, lactulose, fructo-oligosaccharides, and transgalacto-oligosaccharides, which are considered to be easily fermentable carbohydrates by beneficial bacteria in the hindgut. Prebiotics have been found to be efficient against pathogenic bacteria in pigs (Tran et al., 2016) and most prebiotic effects have been consistent at the gut level (van der Aar et al., 2017). However, results in performance have been inconsistent with use of prebiotics, probably due to differences in stage of production, health status, and husbandry practices (Jacela et al., 2010a; Liu et al., 2018).
Direct-fed microbials

Direct-fed microbials, commonly known as DFM or probiotics, are live microorganisms that, when provided in adequate amounts in the diet, can improve gut microbial balance (Fuller, 1989). Direct-fed microbials are generally categorized into: Bacillus-based, lactic acid-producing bacteria, and yeasts (Stein and Kil, 2006).

Bacillus-based DFM are spore-forming bacteria. Spores are thermostable and survive at low pH, which makes Bacillus-based DFM stable during feed processing and gastric digestion. Bacillus-based DFM produce spores that germinate but do not proliferate in the intestine, which means a constant supply of DFM is required to maintain the microbial population. Lactic acid-producing bacteria are not spore-forming and include Lactobacillus acidophilus, Bifidobacterium bifidum, and Enterococcus faecium. Lactic acid-producing bacteria are able to proliferate in the intestine and sustain a microbial population. However, survival during feed processing is of concern because lactic acid-producing bacteria are not thermostable. Direct-fed microbials are available as a single-species or single-strain product, but most commercial products contain more than one species, strains, and even a combination with yeasts and prebiotics (Liao and Nyachoti, 2017).

Direct-fed microbials, similar to prebiotics, increase the beneficial gut bacterial population mostly by increasing short chain fatty acids (SCFA) production. Short chain fatty acids lower the pH, reduce enteric pathogens, and also stimulate intestinal cell proliferation which maintains gut integrity. The increase in the population of beneficial bacteria also controls enteric pathogens by competitive exclusion. However, the mode of action of DFM seems to be even more comprehensive (Liao and Nyachoti, 2017).

Direct-fed microbials have sometimes been associated with performance improvements when added to swine diets (Zimmermann et al., 2016). Apparently, lactic acid-producing bacteria appear to be more beneficial for weanling pigs to help on gut microbial balance after weaning, whereas Bacillus-based DFM seem to be more beneficial for growing-finishing pigs to increase the digestibility of energy and nutrients in high-fiber diets (Liu et al., 2018). However, the effects of DFM in performance are often inconsistent, probably due to the variation in microbial strains, inclusion rate, feeding duration, as well as stage of production, health status, and husbandry practices (Liao and Nyachoti, 2017). Thus, it is difficult to generalize in terms of the effects of DFM on swine diets.

A concern with use of DFM is the transfer of antibiotic resistance genes to pathogenic bacteria (Amachawadi et al., 2018). Commercial DFM products should identify the probiotics to the strain level and ensure the probiotics do not harbor any transferable antibiotic resistance genes.

Yeasts

Yeast cultures are also DFM and the most commonly used in swine diets include Aspergillus oryzae, Candida pintoilopesii, Saccharomyces boulardii, and Saccharomyces cerevisiae. Yeasts are mainly used as live yeast cultures or yeast derivatives like yeast cell walls. The polysaccharides that constitute the yeast cell walls, notably β-glucans and α-mannans, are believed to be the primary reason for the effects of yeasts (Kogan and Kocher, 2007).

The exact mode of action and properties of yeast cell walls have not been fully understood but are believed to be related to improvements in resistance against enteric infections and modulation of immunity. Yeast cell walls appear to improve gut health by inhibiting colonization of enteric pathogens by blocking their binding sites in gut cells. Yeast cell walls also seem to enhance immunity by stimulation of immune cell function, upregulation of cytokines, and antioxidant activity (Kogan and Kocher, 2007). Another property of yeast cell walls is the toxin-binding capacity, which is mainly explored as mycotoxins adsorbents.

The effects of supplementing diets with yeasts and yeast derivatives on health and performance of pigs are ambiguous. There is evidence to support an improvement in resistance against enteric infections and growth performance of nursery pigs (Shen et al., 2009; Kiarie et al., 2011; Kiros et al., 2018), but these effects are often inconsistent (Liu et al., 2018). In grower-finisher pigs, the effects of yeast on performance have been unremarkable (Keegan et al., 2005; Kerr et al., 2013).

Phytogenics

Phytogenics are plant-derived compounds that include a vast variety of compounds, such as herbs, spices, oleoresins, and essential oils. The composition and concentration of active substances vary widely depending on plant, plant part, geographical origin, harvesting season, storage conditions, and processing techniques (Windisch et al., 2008). The extraction of essential oils is the most predominant plant processing technique. Essential oils contain a mixture of various
compounds in different concentrations. The main constituents of essential oils used in swine diets are phenols and terpenes, including anethol, capsaicin, carvacrol, cinnamaldehyde, curcumin, eugenol, and thymol (Zeng et al., 2015).

The exact mode of action and properties of phytogenics have not been fully understood, but are believed to be mostly related to the antimicrobial action, anti-inflammatory activity, and antioxidant effect of phytogenics. Additionally, phytogenics are often claimed to improve the feed flavor and palatability, which could lead to an increase in voluntary feed intake and growth performance (Windisch et al., 2008), although not well established.

The addition of phytogenics to swine diets have sometimes been associated with improvements in performance (Windisch et al., 2008; Zeng et al., 2015). However, the effects of phytogenics on performance have not been consistent (Liu et al., 2018; Soto et al., 2018). There is need for a systematic approach to determine the composition, understand the mode of action, and evaluate the efficiency of phytogenic products. Additionally, safety of phytogenic compounds and potential interactions with feed ingredients and other feed additives warrants further consideration (Jacela et al., 2010a).

Enzymes

Enzymes are active proteins that accelerate the breakdown of specific feed components to release nutrients for digestion and absorption. Enzymes are typically used in swine diets to degrade feed components resistant to endogenous enzymes, inactivate antinutritional factors, and supplement endogenous enzymes that are not present in sufficient amounts (Thacker, 2013). Enzymes typically have designations with the suffix “ase” and are commonly produced by bacteria, fungi, or yeast. The most commonly used enzymes in swine diets are phytase, carbohydrases, and proteases (Jacela et al., 2009b). Phytase is certainly the most widely used among the enzymes due to its efficacy in releasing phosphorus from phytate. Phytase is reviewed in a single topic (Phytase in Swine Diets), while carbohydrases and proteases are detailed here.

Carbohydrases are enzymes that degrade carbohydrates, which include starch and non-starch polysaccharides. Non-starch polysaccharides are components of the cell walls of plant ingredients that are not degradable by the pig, including cellulose, hemicellulose, pectins, α-galactosides, β-glucans, and xylans. Carbohydrases most commonly used in swine diets are β-glucanase and xylanase, but α-amylase, cellulase, pectinase, α-galactosidase, β-mannanase, and others are also commercially available (Thacker, 2013). The use of carbohydrases could provide potential benefits particularly in diets formulated with the addition of ingredients with greater concentration of non-starch polysaccharides, such as barley, wheat, and grain co-products like distillers dried grains with solubles (Jacela et al., 2010c; Jones et al., 2010). Carbohydrases could improve the nutritional value or allow greater inclusion rate of these ingredients in the diet.

Proteases are enzymes that degrade proteins and act on protein-based anti-nutritional factors. Proteases used in swine diets have the ability to degrade a wide range of proteins, including less digestible proteins, such as glycinin and β-conglycinin in soybean meal-based diets (Chen et al., 2017). Proteases are often added to the diet in combination with carbohydrases, but single proteases are also commercially available (Zuo et al., 2015). The use of proteases could provide potential benefits particularly in the nursery, as pigs experience a decrease in enzymatic activity at weaning. Moreover, proteases could aid in the digestion of soybean proteins that are less digestible by weanling pigs and in the degradation of soybean allergens, particularly glycinin and β-conglycinin (Zuo et al., 2015).

Carbohydrases and proteases have often been shown to improve digestibility of nutrients and availability of energy of feed ingredients (Kiari et al., 2007; Emiola et al., 2009; Zuo et al., 2015). Recently, xylanase has been associated with a potential reduction in finisher mortality (Zier-Rush et al., 2016). However, the ability of in-feed enzymes to improve performance has not been proven consistent (Jacela et al., 2009b; Jacela et al., 2010c; Jones et al., 2010; Torres-Pitarch et al., 2017). The inconsistent effects of in-feed enzymes on performance could be due to denaturation of enzymes in the stomach, prompting the use of enzymes that are active over a broad pH range and are resistant to the action of gastric enzymes (Thacker, 2013). Moreover, the type and level of enzymes in a commercial product should match the type and level of substrates present in the feed ingredients included in the diet to achieve a better response to in-feed enzymes. For example, diets based on wheat probably would respond more to added xylanase, while barley would respond more to β-glucanase (Jacela et al., 2009b). Ultimately, the inclusion of enzymes in swine diets needs to be economically justified.
Pharmacological levels of zinc and copper

Zinc and copper are trace minerals required at concentrations of 50 to 110 ppm and 5 to 10 ppm, respectively, to meet the nutrient requirement of pigs. However, the addition of zinc and copper at quantities greater than the requirement exerts a beneficial effect on growth performance of nursery and grow-finish pigs (Liu et al., 2018). Greater quantities of zinc and copper are often referred as growth promoting or pharmacological levels.

Pharmacological levels of dietary zinc between 2,000 and 3,000 ppm is a common recommendation to nursery diets to reduce post-weaning diarrhea and improve growth performance (Hill et al., 2000; Shelton et al., 2011). The maximum tolerable dietary level for swine is generally set at 1,000 ppm with the exception of zinc oxide, which may be included at higher levels (NRC, 2012) for short periods of time immediately after weaning. The grow-promoting effects have been consistently demonstrated with dietary zinc provided as zinc oxide (ZnO) (Hill et al., 2001; Hollis et al., 2005; Walk et al., 2015), while zinc sulfate (ZnSO₄) has greater potential to induce toxicity (Hahn and Baker, 1993). Organic sources of zinc with greater bioavailability have not consistently demonstrated the same benefits as zinc oxide when organic zinc is added at lower levels (Hahn and Baker, 1993; Carlson et al., 2004; Hollis et al., 2005). The mode of action of pharmacological levels of zinc to improve growth performance seems to be related to antimicrobial activity, antioxidant capacity, development of gut morphology, and maintenance of gut integrity (Højberg et al., 2005; Zhu et al., 2017). However, pharmacological levels of zinc appear to interfere with calcium and phosphorus absorption, prompting the use of phytase or greater levels of calcium and phosphorus in the diet to ameliorate this effect (Blavi et al., 2017).

Pharmacological levels of dietary copper between 125 and 250 ppm are commonly used in the diet to enhance fecal consistency in nursery pigs and improve growth performance in both nursery and grow-finish pigs (Bikker et al., 2016; Coble et al., 2017). The most commonly used source of dietary copper is copper sulfate (CuSO₄) (Cromwell et al., 1998), but tribasic copper chloride (TBCC) is as effective as copper sulfate in promoting growth performance (Cromwell et al., 1998; Coble et al., 2017). Organic sources of copper with greater bioavailability, such as Cu-amino acid chelate, also seem to have the potential to influence growth performance (Pérez et al., 2011; Carpenter et al., 2018). The mode of action of dietary copper to improve growth performance appears to be mainly attributed to antimicrobial activity (Højberg et al., 2005).

A typical recommendation is to use pharmacological levels of zinc in initial nursery diets fed to pigs up to 25 lb and then replace zinc by pharmacological levels of copper for the remaining nursery period. In the grow-finish period, pharmacological levels of copper but not zinc can be used. Additive effects of using pharmacological levels of zinc and copper are not common (Hill et al., 2000), but might occur to some degree (Pérez et al., 2011). In diets with in-feed antimicrobials, the use of pharmacological levels of zinc or copper seems to have an additive effect in growth performance (Stahly et al., 1980; Hill et al., 2001).

The use of pharmacological levels of zinc and copper poses an environmental concern because of the greater excretion of minerals in swine waste and ultimately in the soil fertilized with swine manure (Jondreville et al., 2003). In addition, the implication of pharmacological levels of zinc and copper as a cause of increasing antimicrobial resistance is a rising concern (Yazdankhah et al., 2014). Therefore, regulations have been implemented in some countries restricting or prohibiting the use of zinc or copper as growth promoters. Thus, there is an appeal for prudent use of pharmacological levels of zinc and copper in swine production.

Medium-chain fatty acids

Medium-chain fatty acids (MCFA) are saturated fatty acids with 6 to 12 carbon in length, and are caproic (C6), caprylic (C8), capric (C10), and lauric (C12) acids. Medium-chain fatty acids occur naturally in triglycerides of various feed ingredients, especially coconut oil and palm oil, but are commercially available as single MCFA or blends of MCFA. The characteristics of medium-chain fatty acids include easy digestion and rapid absorption, which makes MCFA a readily available source of energy for the pig (Zentek et al., 2011).

The inclusion of MCFA in swine diets have demonstrated a potential to improve growth performance and gut health particularly in nursery pigs (Zentek et al., 2011; Gebhardt et al., 2017). Medium-chain fatty acids provide a readily available source of energy, which can be utilized by the pig for growth or by the gut cells to improve gut development and integrity (Zentek et al., 2011; Liu, 2015). The effects of MCFA on growth performance are greatly dependent on MCFA type, purity, and inclusion rate in the diet (Gebhardt et al., 2017). Improvements in nursery performance have been demonstrated with 0.50% inclusion of C6 or C8 as well as...
with 0.25, 0.50, 1.0 or 1.50% inclusion of a 1:1:1 blend of C6, C8, and C10 (Gebhardt et al., 2017).

In addition, MCFA are able to inactivate bacteria and virus (Zenkey et al., 2011; Hanczakowska, 2017), contributing to both gut health and feed safety (Liu, 2015; Cochrane et al., 2017; Gebhardt et al., 2018a).

Chromium

Chromium is an essential trace mineral primarily involved in the metabolism of glucose. Chromium potentiates the action of insulin by facilitating the binding of insulin to receptors and thus improving glucose utilization (NRC, 2012). Feed ingredients commonly used in swine diets contain a significant amount of chromium, ranging from 1,000 to 3,000 ppb, but bioavailability is typically low. Organic sources of chromium, such as chromium picolinate, chromium nicotinate, chromium propionate, and chromium yeast, are more bioavailable and more utilized in swine diets than inorganic sources, such as chromium chloride. The use of chromium sources is legally allowed in swine diets up to 200 ppb according to a letter of non-objection from the Food and Drug Administration. Dietary addition of chromium is most often targeted to finishing pigs and sows.

Addition of chromium to diets for finishing pigs has been related to improvements in growth performance and carcass leanness, with no impact on characteristics related to pork quality (Lindemann et al., 1995; Lien et al., 2001; Sales and Jančík, 2011; Gebhardt et al., 2018b). The mechanism of chromium to improve lean deposition is not clear, but it could be due to the stimulation of protein deposition and lipid degradation as a response to insulin activity (Lien et al., 2001). However, the effects of chromium on grow-finish pigs have been modest (Gebhardt et al., 2018b) and not consistent (Mooney and Cromwell, 1999; Shelton et al., 2003; Matthews et al., 2005; Kim et al., 2009). The variation in chromium status of the pig, amount of available chromium in the diet, and environmental conditions could contribute to inconsistency. Due to this variability and inconsistency in performance, there is currently no estimate for chromium requirements for swine (NRC, 2012).

Addition of chromium to diets for sows has been related to an increase in litter size (Lindemann et al., 1995; Lindemann et al., 2004; Wang et al., 2013). The ability of chromium to increase litter size is primarily associated to the influence of insulin and glucose on nutritional status and reproductive hormones of sows before breeding (Cox et al., 1987; Whitley et al., 2002; Woodworth et al., 2007). The magnitude of the effect of chromium on litter size is dependent on dose and feeding duration, but the improvement on sow prolificacy is generally consistent.

Additive effects of supplementation of sow diets with chromium and carnitine have been found on reproductive performance (Real et al., 2008). Both chromium and carnitine influence energy metabolism of sows but through different mechanisms that seem to act synergistically (Woodworth et al., 2007). The supplementation of sow diets with chromium and carnitine has been shown to additively improve farrowing rate and thus number of piglets born alive (Real et al., 2008).

Carnitine

Carnitine is a vitamin-like compound involved in the transport of fatty acids into the mitochondria to produce energy. Carnitine is synthesized from lysine and methionine and derived from the diet (Fischer et al., 2009). Only the L-isomer of carnitine is active for swine. Dietary addition of carnitine is most often targeted to grow-finish pigs and sows.

Addition of carnitine to diets for sows has been shown to improve growth performance and carcass leanness (Owen et al., 2001a; James et al., 2013a; Ying et al., 2013). The effects of carnitine in grow-finish pigs have been attributed to an enhancement in the ability to efficiently use fat for energy and to synthesize amino acids and proteins (Owen et al., 2001b). To the pig, this translates into improved growth rate and efficiency, decreased lipid deposition, and increased protein accretion (Heo et al., 2000). However, the effects of carnitine in grow-finish pigs have been inconsistent (Owen et al., 2001a,b; Pietruszka et al., 2009; James et al., 2013b). It’s been suggested that factors that affect energy intake, such as stocking density, health status, and environmental temperature, as well as the amino acid levels in the diet could influence the effects of carnitine in grow-finish pigs (Ying et al., 2013).

Addition of carnitine to diets for sows has been shown to increase birth weight and weaning weight of piglets and litters (Musser et al., 1999; Ramanau et al., 2004; Ramanau et al., 2008; Wei et al., 2018). Carnitine has also been shown to improve litter size and reduce the number of stillborn or non-viable piglets (Musser et al., 1999; Eder et al., 2001; Ramanau et al., 2004; Zhang et al., 2018), although less consistently. There are many mechanisms by which carnitine acts to increase birth weight, but are mainly involved with improvement of
Betaine

Betaine is an amino acid derivative that serves as a methyl donor in metabolic processes. Betaine provides methyl groups (\(–\text{CH}_3\)) for the synthesis of many compounds, such as creatine and carnitine, and decrease the requirement for other methyl donors, such as methionine and choline. Betaine is also an osmotically active compound that regulates water movement and electrolyte balance, providing osmotic protection for many cells, including intestinal cells and muscle fibers (Eklund et al., 2005). Betaine can be produced by chemical synthesis or as a by-product of sugar beet processing. Betaine is commercially available as anhydrous betaine, betaine monophosphate, and betaine hydrochloride (Eklund et al., 2005).

Addition of betaine to grow-finish diets has been demonstrated to improve growth performance, carcass leaness, and pork quality (Matthews et al., 2001a,b), but the effects of betaine have been inconsistent (Sales, 2011). The mode of action of betaine have not been fully understood, but it has been suggested that betaine may have an energy-sparing effect that improves growth and protein deposition (Schrama et al., 2003) and an osmoprotective effect that improves pork quality (Eklund et al., 2005). The osmo-protectant capacity of betaine may also improve nutrient digestibility and gut health (Eklund et al., 2005), and enhance the ability of grow-finish pigs to cope with heat stress (Mendoza et al., 2017a,b).

Addition of betaine to sow diets has been demonstrated to potentially improve reproductive performance, but there is little evidence to support consistent effects (Ramis et al., 2011; van Wettere et al., 2013). There is growing interest to supplement betaine in sow diets during summer (van Wettere et al., 2012, Cabezón et al., 2016; 2017). Betaine is believed to improve lactation feed intake, reduce wean-to-estrus interval, and enhance embryo survival during heat stress (van Wettere et al., 2012, Cabezón et al., 2016). It’s been suggested that betaine may ameliorate the effect of heat stress on sows due to an energy-sparing effect that improves energy utilization and an osmo-protectant effect that increases water retention and regulates electrolyte balance (Cabezón et al., 2016). However, the benefits of betaine supplementation on reproductive performance of sows require further research before a definitive recommendation can be made.

Conjugated linoleic acid

Conjugated linoleic acid (CLA) is a term for isomers of linoleic acid (C18:2). The function of CLA involves regulation of body composition and energy retention (Müller et al., 2000).

Addition of CLA to grow-finish diets has been related to improvements in growth performance, carcass leaness, and fat firmness (Eggert et al., 2001; Thiel-Cooper et al., 2001; Larsen et al., 2009). The mode of action of CLA involves the regulation of enzymes and gene expression in lipid metabolism (Jiang et al., 2010). Also, CLA increases the proportion of saturated to unsaturated fatty acids in fat, which leads to greater fat firmness (Larsen et al., 2009). There is a nutritional opportunity for addition of CLA to grow-finish diets to offset the issues of fat softness and iodine value that arise from diets with unsaturated fatty acid sources, such as diets with distillers dried grains with solubles (White et al., 2006; Brown et al., 2008). There is growing interest to supplement CLA to sow diets during summer (van Wettere et al., 2012, Cabezón et al., 2016; 2017). Conjugated linoleic acid-rich pork products have been shown to provide health benefits and may have an appeal to consumers.
Kapok oil

Kapok oil is extracted from seeds of kapok (Ceiba pentandra), a tropical tree. Kapok oil is rich in cyclopropenoid fatty acid, which is able to reduce desaturation of fatty acids and thus increase saturated fatty acids in oils (Yu et al., 2011; Anwar et al., 2014). Addition of kapok oil to diets for grow-finish pigs has been related to improvements in pork fat firmness (Maeda et al., 2017). Similar to conjugated linoleic acid, there is a nutritional opportunity for the addition of kapok oil to grow-finish diets to offset the issues of fat softness and iodine value that arise from diets containing high concentrations of unsaturated fatty acids from ingredients such as distillers or vegetable oils.

Ractopamine

Ractopamine hydrochloride is a phenethanolamine β-adrenergic agonist that redirects nutrients away from fat deposition and towards protein deposition. It is legally must be made when withdrawal. Also, appropriate nutritional adjustments beneficial effects of ractopamine are quickly lost after should be continuously supplied up to marketing as the marketing, which is about 21 to 35 days. Ractopamine at 5 to 10 mg/kg for the last 45 to 90 days to support greater rate of lean gain. It is legally required that diets with ractopamine contain at least 16% crude protein. It is recommended to increase lysine levels by 5 to 6 g of SID Lys per day (0.2 to 0.25 percentage units of SID Lys) while maintaining other amino acids at a proper ratio to lysine (Jacela et al., 2009b).

Use of ractopamine has raised concerns regarding swine welfare, particularly on behavior, ease of handling, susceptibility to stress, and incidence of fatigued, non-ambulatory market-weight pigs (Marchant-Forde et al., 2003). Finishing pigs fed ractopamine have been found to be more difficult to handle and more susceptible to fatigue and stress with aggressive handling, especially at high inclusion of ractopamine (James et al., 2013c; Ritter et al., 2017). Implementation of low stress handling and transportation practices is particularly important with pigs fed ractopamine in order to safeguard welfare and minimize losses.

Antioxidants

Antioxidants are compounds that reduce the oxidative degradation of fatty acids, i.e. fats and oils. Antioxidants thus can be added to fats and oils to reduce oxidation of fats and oils. However, antioxidants cannot reverse fat oxidation once it occurs (Kerr et al., 2015).

Antioxidants are classified by mode of action into primary and secondary antioxidants based on effects on which stage of fat oxidation. Fat oxidation is described in three stages: initiation, propagation, and termination, with different compounds produced in each stage (Shurson et al., 2015). Primary antioxidants inhibit the initiation and delay the propagation of fat oxidation, and are most effective in the early stages of oxidation. Primary antioxidants are natural carotenoids, flavonoids, tocopherols, and synthetic ethoxyquin, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), propyl gallate, among others (Kerr et al., 2015).

Secondary antioxidants slow the rate of fat oxidation and are effective in different stages of oxidation. Secondary antioxidants are citric acid and ethylenediamine-tetra-acetic acid (EDTA), among others (Kerr et al., 2015).

Commercial antioxidant products commonly include a combination of antioxidants with synergistic activity to improve efficacy (Jacela et al., 2010b).

Antioxidants have been used to ameliorate the impact of fat oxidation on growth performance (Lu et al., 2014), although the benefits have not been consistent (Song et al., 2014). Also, antioxidant addition in swine diets have been used to control rancidity, which could help to maintain palatability and prolong storage time (Kerr et al., 2015). In that sense, the use of antioxidants may be more important in diets with high amounts of added fat and diets manufactured in warm climates (Jacela et al., 2010b). Regular analysis of fat sources important to provide an accurate assessment of the degree of fat oxidation and rancification.
Mycotoxin binders

Mycotoxins are toxic compounds produced by mold growth in feed ingredients. The most significant mycotoxins affecting swine are aflatoxin, vomitoxin, zearalenone, fumonisin, and ochratoxin, which are produced by molds that belong to the genera *Aspergillus*, *Fusarium*, and *Penicillium*. Mycotoxin contamination prevention includes pre- and post-harvest strategies. Interventions carried out in the field to prevent fungal infestation, such as crop rotation, tillage, insect control, and fungicides, are the most effective but often insufficient to prevent mycotoxin contamination (Jard et al., 2011). After harvest, one effective intervention is to screen and clean grain to reduce mycotoxin contamination in grains (Yoder et al., 2017). The most prevalent intervention is the inclusion of mold inhibitors and mycotoxin binders in the feed (Vila-Donat et al., 2018).

Mold inhibitors are used to control mold contamination and prevent mold growth in order to minimize the risk of having mycotoxin-producing molds in grain or feed (Jacela et al., 2010b). Acidifiers are commonly used as mold inhibitors, particularly organic acids such as propionic acid. Acidifiers display fungicidal properties by reducing the pH in grain and feed (Suiryanrayna and Ramana, 2015). However, the use of acidifiers as mold inhibitors have no effect on mycotoxins already present in contaminated grain and feed (Jacela et al., 2010b).

Mycotoxin binders or adsorbents are substances that bind to mycotoxins and prevent absorption through the gut (Table 1). The most commonly used mycotoxin binders in swine feeds are aluminosilicate binders, which include clays, bentonites, zeolites, and hydrated sodium calcium aluminosilicate (HSCAS). The aluminosilicate binders are natural, inorganic mycotoxin binders containing a porous structure made of silica that is able to adsorb and trap mycotoxins (Jouany, 2007; Di Gregorio et al., 2014). The aluminosilicate binders are very effective aflatoxin binders, but have limited activity against other types of mycotoxins (Huwig et al., 2001; Jiang et al., 2012; Vila-Donat et al., 2018). Furthermore, aluminosilicate binders are nonspecific and bind vitamins and trace minerals as well (Huwig et al., 2001; Vila-Donat et al., 2018).

Other mycotoxin binders used in swine feeds are yeast components. The yeast components are natural, organic mycotoxin binders extracted from the cell walls of *Saccharomyces cerevisiae*, primarily α-mannans and β-glucans (Jouany, 2007). The yeast components have a diverse mechanism of adsorption and act against a wide range of mycotoxins (Huwig et al., 2001). Furthermore, organic yeast components are biodegradable and do not accumulate in the environment after being excreted in the manure, in contrast to inorganic silicate binders (Jouany, 2007).

However, mycotoxin binders are vastly ineffective against vomotoxin (Dänicke, 2002; Döll and Dänicke, 2003; Frobose et al., 2015). Vomitoxin is the colloquial term for deoxynivalenol (DON), the most common contaminant of grains and feed (Rodrigues and Naehrer, 2012). Recently, sodium metabisulfite has been found to be a promising agent against vomitoxin (Frobose et al., 2017; Shawk et al., 2018). Although not approved by Food and Drug Administration as a DON-detoxifying agent, sodium metabisulfite reacts with DON to form a non-toxic component in a process that requires heat and humidity for optimal efficiency (Young et al., 1987). The addition of sodium metabisulfite to diets naturally contaminated with vomitoxin seems to restore feed intake and improve growth performance of nursery pigs (Frobose et al., 2017; Shawk et al., 2018). However, sodium metabisulfite is known to degrade the vitamin thiamin, which needs to be supplemented in diets with sodium metabisulfite.

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<tr>
<th>Mycotoxin type</th>
<th>Effective mycotoxin binder</th>
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<tr>
<td>Aflatoxins</td>
<td>Aluminosilicates/Bentonites¹</td>
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<tr>
<td>Vomitoxin (DON)</td>
<td>Sodium metabisulfite²</td>
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<tr>
<td>Zearalenone</td>
<td>Limited efficacy data with Aluminosilicates/Clays³</td>
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<tr>
<td>Fumonisins</td>
<td>Lacking consistent efficacy data</td>
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<td>Ochratoxin A</td>
<td>Lacking consistent efficacy data</td>
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</table>

¹From Harper et al. (2010).
²From Frobose et al. (2017) and Shawk et al. (2018).
³From Jiang et al. (2012).
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