Feed Additives in Swine Diets

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 consider 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 weaning 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 pintolopesii*, *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, cinnalmaldehyde, 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 stablished.

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-amilase, 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 ($ZnSO_4$) 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 ($CuSO_4$) (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 (Zentek 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 in grow-finish diets 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

nutrient supply and muscle development of fetus via increased concentration of insulin-like growth factors (IGF-1 and IGF-2), enhanced placental development, and improved supply of glucose via placenta (Doberenz et al., 2006; Woodworth et al., 2007; Brown et al., 2008; Eder, 2009; Zhang et al., 2018). In addition, there are other mechanisms by which carnitine acts to increase weaning weight, which are mainly involved with improvement in milk production, milk composition, and suckling behavior (Ramanau et al., 2004; Birkenfeld et al., 2006; Zhang et al., 2018). Recently, carnitine has been associated with enhancement of the antioxidant status of sows and piglets (Wei et al., 2018).

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

Betaine

Betaine is an amino acid derivative that serves as a methyl donor in metabolic processes. Betaine provides methyl groups ($—CH_3$) 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 sugarbeet 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 leanness, 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 osmo-protectant 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 leanness, 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., 2009).

Another potential benefit of feeding CLA to grow-finish pigs is the incorporation of CLA in pork products (Dugan et al., 2004). 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 dried grains with solubles or vegetable oils.

Ractopamine

Ractopamine hydrochloride is a phenethanolamine β-adrenergic agonist that redirects nutrients away from fat deposition and towards lean deposition. The mode of action of ractopamine primarily involves the modulation of metabolic pathways and signals in muscle and lipid cells to enhance protein accretion. Other mechanisms also include regulation of hormone release and modification of blood flow (Mersmann, 1998).

Ractopamine inclusion in finishing diets has been consistently related to improvements in growth rate, feed efficiency, and carcass leanness with minimal effects on pork quality (Apple et al., 2007; Bohrer et al., 2013). Ractopamine seems to enhance lean gain by partitioning energy towards protein deposition, which also improves efficiency because protein requires less energy to be deposited than fat (Mersmann, 1998). The effects of ractopamine progressively decrease over time as prolonged exposure to β-adrenergic agonist causes desensitization of receptors (Mersmann, 1998). Also, the effects of ractopamine are lost once the inclusion of ractopamine in the diet is stopped.

Ractopamine is labeled for addition to finishing diets at 5 to 10 mg/kg for the last 45 to 90 lb of gain before marketing, which is about 21 to 35 days. Ractopamine should be continuously supplied up to marketing as the beneficial effects of ractopamine are quickly lost after withdrawal. Also, appropriate nutritional adjustments must be made when adding ractopamine in finishing diets 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 rancidification.

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 proliferation of 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.

Table 1. Effective mycotoxin binders based on efficacy demonstration in pigs	
Mycotoxin type	**Effective mycotoxin binder**
Aflatoxins	Aluminosilicates/Bentonites[1]
Vomitoxin (DON)	Sodium metabisulfite[2]
Zearalenone	Limited efficacy data with Aluminosilicates/Clays[3]
Fumonisins	Lacking consistent efficacy data
Ochratoxin A	Lacking consistent efficacy data

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

References

Amachawadi, R. G., F. Giok, X. Shi, J. Soto, S. K. Narayanan, M. D. Tokach, M. D. Apley, and T. G. Nagaraja. 2018. Antimicrobial resistance of *Enterococcus faecium* strains isolated from commercial probiotic products used in cattle and swine. Journal of Animal Science. 96:912–920. doi:10.1093/jas/sky056

Anwar, F., U. Rashid, S. A. Shahid, and M. Nadeem. 2014. Physicochemical and antioxidant characteristics of kapok (*Ceiba pentandra* Gaertn.) seed oil. Journal of the American Oil Chemists' Society. 91:1047-1054. doi:10.1007/s11746-014-2445-y

Apple, J. K., P. J. Rincker, F. K. McKeith, S. N. Carr, T. A. Armstrong, and P. D. Matzat. 2007. Review: Meta-analysis of the ractopamine response in finishing swine. The Professional Animal Scientist. 23:179–196. doi: 10.15232/S1080-7446(15)30964-5

Bikker, P., A. W. Jongbloed, and J. van Baal. 2016. Dose-dependent effects of copper supplementation of nursery diets on growth performance and fecal consistency in weaned pigs. Journal of Animal Science. 94(Suppl. 3)181–186. doi:10.2527/jas.2015-9874

Birkenfeld, C., H. Kluge, and K. Eder. 2006. L-carnitine supplementation of sows during pregnancy improves the suckling behaviour of their offspring. British Journal of Nutrition. 96:334–342. doi:10.1079/BJN20061833

Blavi, L., D. Sola-Oriol, J. F. Perez, and H. H. Stein. 2017. Effects of zinc oxide and microbial phytase on digestibility of calcium and phosphorus in maize-based diets fed to growing pigs. Journal of Animal Science. 95:847-854. doi:10.2527/jas.2016.1149

Bohrer, B. M., J. M. Kyle, D. D. Boler, P. J. Rincker, M. J. Ritter, and S. N. Carr. 2013. Meta-analysis of the effects of ractopamine hydro-chloride on carcass cutability and primal yields of finishing pigs. Journal of Animal Science. 91:1015–1023. doi:10.2527/jas.2012-5647

Brown, K. R., R. D. Goodband, M. D. Tokach, S. S. Dritz, J. L. Nelssen, J. E. Minton, J. J. Higgins, X. Lin, J. Odle, J. C. Woodworth, and B. J. Johnson. 2008. Effects of feeding L-carnitine to gilts through day 70 of gestation on litter traits and the expression of insulin-like growth factor system components and L-carnitine concentration in foetal tissues. Journal of Animal Physiology and Animal Nutrition. 92:660–667. doi:10.1111/j.1439-0396.2007.00762.x

Cabezón, F. A., A. P. Schinckel, B. T. Richert, K. R. Stewart, M. Gandarillas, M. Pasache, and W. A. Peralta. 2016. Effect of betaine supplementation during summer on sow lactation and subsequent farrowing performance. The Professional Animal Scientist. 32:695–703. doi.10.15232/pas.2016-01532

Cabezón, F. A., A. P. Schinckel, K. R. Stewart, B. T. Richert, M. Gandarillas, J. N. Marchant-Forde, J. S. Johnson, W. A. Peralta, and R. M. Stwalley. 2017. Heat stress alleviation in lactating sows by dietary betaine supplementation and cooling pads, Journal of Animal Science. 95(Suppl. 2):116–117. doi:10.2527/asasmw.2017.243

Carlson, M. S., C. A. Boren, C. Wu, C. E. Huntington, D. W. Bollinger, and T. L. Veum. 2004. Evaluation of various inclusion rates of organic zinc either as polysaccharide or proteinate complex on the growth performance, plasma, and excretion of nursery pigs. Journal of Animal Science. 82:1359–1366. doi:10.2527/2004.8251359x

Carpenter, C. B., J. C. Woodworth, J. M. DeRouchey, M. D. Tokach, R. D. Goodband, S. S. Dritz, F. Wu, and J. L. Usry. 2018. Effects of increasing copper from tri-basic copper chloride or a copper-methionine chelate on growth performance of nursery pigs. Translational Animal Science. doi:doi.org/10.1093/tas/txy091

Chen, H., S. Zhang, I. Park, and S. W. Kim. 2017. Impacts of energy feeds and supplemental protease on growth performance, nutrient digestibility, and gut health of pigs from 18 to 45 kg body weight. Animal Nutrition. 3:359-365. doi:10.1016/j.aninu.2017.09.005

Coble, K. F., J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, J. C. Woodworth, and J. L. Usry. 2017. The effects of copper source and concentration on growth performance, carcass characteristics, and pen cleanliness in finishing pigs. Journal of Animal Science. 95:4052–4059. doi:10.2527/jas2017.1624

Cochrane, R. A., S. S. Dritz, J. C. Woodworth, A. R. Huss, C. R. Stark, M. Saensukjaroenphon, J. M. DeRouchey, M. D. Tokach, R. D. Goodband, J. F. Bai, Q. Chen, J. Zhang, P. C. Gauger, R. J. Derscheid, R. G. Main, and C. K. Jones. 2017. Assessing the effects of medium chain fatty acids and fat sources on PEDV RNA stability and infectivity. Journal of Animal Science. 95(Suppl. 2):94. doi:10.2527/asasmw.2017.12.196

Cox, N. M., M. J. Stuart, T. G. Althen, W. A. Bennett, and H. W. Miller. 1987. Enhancement of ovulation rate in gilts by increasing dietary energy and administering insulin during follicular growth. Journal of Animal Science. 64:507–516.

Cromwell, G. L., M. D. Lindemann, H. J. Monegue, D. D. Hall, and D. E. Orr Jr. 1998. Tribasic copper chloride and copper sulfate as copper sources for weanling pigs. Journal of Animal Science. 76:118-123. doi:10.2527/1998.761118x

Dänicke, S. 2002. Fusariums toxins in animal nutrition. Lohmann Information. 27:29–37. Available at: http://lohmann-information.com/content/l_i_27_article_5.pdf

Di Gregorio, M. C., D. V. de Neeff, A. V. Jager, C. H. Corassin, Á. C. de P. Carão, R. de Albuquerque, A. C. de Azevedo, and C. A. F. Oliveira. 2014. Mineral adsorbents for prevention of mycotoxins in animal feeds. Toxin Reviews. 33:125–135. doi:10.3109/15569543.2014.905604

Doberenz, J., C. Birkenfeld, H. Kluge, and K. Eder. 2006. Effects of L-carnitine supplementation in pregnant sows on plasma concentrations of insulin-like growth factors, various hormones and metabolites and chorion characteristics Journal of Animal Physiology and Animal Nutrition. 90:487–499. doi:10.1111/j.1439-0396.2006.00631.x

Döll, S., and S. Dänicke. 2003. On the efficacy of detoxifying agents in the prevention of fusariotoxicosis - A critical evaluation of the situation. Mycotoxin Research. 19:185-189. doi:10.1007/bf02942962

Dugan, M. E., J. L. Aalhus, and J. K. Kramer. 2004. Conjugated linoleic acid pork research. The American Journal of Clinical Nutrition. 79:1212–1216. doi:10.1093/ajcn/79.6.1212S

Eder K., A. Ramanau, and H. Kluge. 2001. Effect of L-carnitine supplementation on performance parameters in gilts and sows. Journal of Animal Physiology and Animal Nutrition. 85:73–80. doi:10.1046/j.1439-0396.2001.00303.x

Eder, K. 2009. Influence of L-carnitine on metabolism and performance of sows. British Journal of Nutrition. 102:645-654. doi:10.1017/S0007114509990778

Eggert, J. M., M. A. Belury, A. Kempa-Steczko, S. E. Mills, and A. P. Schinckel. 2001. Effects of conjugated linoleic acid on the belly firmness and fatty acid composition of genetically lean pigs. Journal of Animal Science. 79:2866–2872. doi:10.2527/2001.79112866x

Eklund, M., E. Bauer, J. Wamatu, and R. Mosenthin. 2005. Potential nutritional and physiological functions of betaine in livestock. Nutrition Research Reviews. 18:31-48. doi:10.1079/NRR200493

Emiola, I. A., F. O. Opapeju, B. A. Slominski, and C. M. Nyachoti. 2009. Growth performance and nutrient digestibility in swine fed wheat distillers dried grains with solubles-based diets supplemented with a multi-carbohydrase enzyme. Journal of Animal Science. 87:2315-2322. doi:10.2527/jas.2008-1195.

Fischer, M., J. Keller, F. Hirche, H. Kluge, R. Ringseis, and K. Eder. 2009. Activities of γ-butyrobetaine dioxygenase and concentrations of carnitine in tissues of pigs. Comparative Biochemistry and Physiology – Part A. 153:324-331. doi:10.1016/j.cbpa.2009.03.005

Frobose, H. L., E. D. Fruge, M. D. Tokach, E. L. Hansen, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, and J. L. Nelssen. 2015. The effects of deoxynivalenol-contaminated corn dried distillers grains with solubles in nursery pig diets and potential for mitigation by commercially available feed additives. Journal of Animal Science. 93:1074–1088. doi:10.2527/jas.2013-6883

Frobose, H.L., E. W. Stephenson, M. D. Tokach, J. M. DeRouchey, J. C. Woodworth, S. S. Dritz, and R. D. Goodband. 2017. Effects of potential detoxifying agents on growth performance and deoxynivalenol (DON) urinary balance characteristics of nursery pigs fed DON-contaminated wheat. Journal of Animal Science. 95:327–337. doi:10.2527/jas.2016.0664

Fuller, R. 1989. Probiotics in man and animals. The Journal of Applied Bacteriology. 66:365-378. doi:10.1111/j.1365-2672.1989.tb05105.x

Gebhardt, J. T., J. C. Woodworth, M. D. Tokach, J. M. DeRouchey, R. D. Goodband, C. K. Jones, and S. S. Dritz. 2018a. Medium chain fatty acid mitigation activity against Porcine Epidemic Diarrhea Virus (PEDV) in nursery pig diets after 40 d of storage. Journal of Animal Science. 96(Suppl. 2):153. doi:10.1093/jas/sky073.282

Gebhardt, J. T., J. C. Woodworth, M. D. Tokach, J. M. DeRouchey, R. D. Goodband, J. A. Loughmiller, A. L. P. de Souza, and S. S Dritz. 2018b. Influence of chromium propionate dose and feeding regimen on growth performance and carcass composition of pigs housed in a commercial environment. Translational Animal Science. txy104. doi:10.1093/tas/txy104

Gebhardt, J. T., K. A. Thomson, J. C. Woodworth, M. D. Tokach, J. M. DeRouchey, R. D. Goodband, and S. S. Dritz. 2017. Evaluation of medium chain fatty acids as a dietary additive in nursery pig diets. Kansas Agricultural Experiment Station Research Reports. 3(7). doi:doi.org/10.4148/2378-5977.7463

Gibson, G. R., and M. B. Roberfroid. 1995. Dietary modulation of the human colonic microbiota: Introducing the concept of prebiotics. The Journal of Nutrition. 125:1401–1412. doi:10.1093/jn/125.6.1401

Gibson, G. R., H. M. Probert, J. van Loo, R. A. Rastall, and M. B. Roberfroid. 2004. Dietary modulation of the human colonic microbiota: updating the concept of prebiotics. Nutrition Research Reviews. 17:259–275. doi:10.1079/NRR200479.

Hahn, J. D., and D. H. Baker. 1993. Growth and plasma zinc responses of young pigs fed pharmacologic levels of zinc. Journal of Animal Science. 71:3020-3024.

Hanczakowska, E. 2017. The use of medium chain fatty acids in piglet feeding – A review. Annals of Animal Science. 17:967-977. doi:10.1515/aoas-2016-0099

Harper, A. F., M. J. Estienne, J. B. Meldrum, R. J. Harrell, and D. E. Diaz. 2010. Assessment of a hydrated sodium calcium aluminosilicate agent and antioxidant blend for mitigation of aflatoxin- induced physiological alterations in pigs. Journal of Swine Health and Production. 18:282-289.

Heo, K., J. Odle, I. K. Han, W. Cho, S. Seo, E. van Heugten, and D. H. Pilkington. 2000. Dietary L-carnitine improves nitrogen utilization in growing pigs fed low energy, fat-containing diets. The Journal of Nutrition. 130:1809–1814. doi:10.1093/jn/130.7.1809

Hill, G. M., D. C. Mahan, S. D. Carter, G. L. Cromwell, R. C. Ewan, R. L. Harrold, A. J. Lewis, P. S. Miller, G. C. Shurson, and T. L. Veum. 2001. Effect of pharmacological concentrations of zinc oxide with or without the inclusion of an antibacterial agent on nursery pig performance. Journal of Animal Science. 79:934–941. doi:10.2527/2001.794934x

Hill, G. M., G. L. Cromwell, T. D. Crenshaw, C. R. Dove, R. C. Ewan, D. A. Knabe, A. J. Lewis, G. W. Libal, D. C. Mahan, G. C. Shurson, L. L. Southern, and T. L. Veum. 2000. Growth promotion effects and plasma changes from feeding high dietary concentrations of zinc and copper to weanling pigs (regional study). Journal of Animal Science. 78:1010–1016. doi:10.2527/2000.7841010x

Højberg, O., N. Canibe, H. D. Poulsen, M. S. Hedemann, and B. B. Jensen. 2005. Influence of dietary zinc oxide and copper sulfate on the gastrointestinal ecosystem in newly weaned piglets. Applied Environmental Microbiology. 71:2267-2277. doi:10.1128/AEM.71.5.2267-2277.2005

Hollis, G. R., S. D. Carter, T. R. Cline, T. D. Crenshaw, G. L. Cromwell, G. M. Hill, S. W. Kim, A. J. Lewis, D. C. Mahan, P. S. Miller, H. H. Stein, and T. L. Veum. 2005. Effects of replacing pharmacological levels of dietary zinc oxide with lower dietary levels of various organic zinc sources for weanling pigs. Journal of Animal Science. 83:2123–2129. doi:10.2527/2005.8392123x

Huwig, A., S. Freimund, O. Käppeli, and H. Dutler. 2001. Mycotoxin detoxication of animal feed by different adsorbents. Toxicology Letters. 122:179-188. doi:10.1016/S0378-4274(01)00360-5

Jacela, J. Y., J. M. DeRouchey, M. D. Tokach, R. D. Goodband, J. L. Nielssen, D. G. Renter, and S. S. Dritz. 2009a. Feed additives for swine: Fact sheet – acidifiers and antibiotics. Journal of Swine Health and Production. 17:270-275.

Jacela, J. Y., J. M. DeRouchey, M. D. Tokach, R. D. Goodband, J. L. Nelssen, D. G. Renter, and S. S. Dritz. 2009b. Feed additive for swine: Fact sheets – carcass modifiers, carbohydrase-degrading enzymes and proteases, and anthelmintics. Journal of Swine Health and Production. 17:325-332.

Jacela, J. Y., J. M. DeRouchey, M. D. Tokach, R. D. Goodband, J. L. Nelssen, D. G. Renter, and S. S. Dritz. 2010a. Feed additives for swine: Fact sheets – prebiotics and probiotics, and phytogenics. Journal of Swine Health and Production. 18:132-136.

Jacela, J. Y., J. M. DeRouchey, M. D. Tokach, R. D. Goodband, J. L. Nelssen, D. G. Renter, and S. S. Dritz. 2010b. Feed additives for swine: Fact sheets – flavors and mold inhibitors, mycotoxin binders, and antioxidants. Journal of Swine Health and Production. 18:27–32.

Jacela, J. Y., S. S. Dritz, J. M. DeRouchey, M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 2010c. Effects of supplemental enzymes in diets containing distillers dried grains with solubles on finishing pig growth performance. The Professional Animal Scientist. 26:412-424. doi:10.15232/S1080-7446(15)30623-9

James, B. W., M. D. Tokach, R. D. Goodband, J. L. Nelssen, S. S. Dritz, K. Q. Owen, J. C. Woodworth, and R. C. Sulabo. 2013a. Interactive effects of dietary ractopamine HCl and L-carnitine on finishing pigs: I. Growth performance. Journal of Animal Science. 91:3265–3271. doi:10.2527/jas.2011-4286

James, B. W., M. D. Tokach, R. D. Goodband, J. L. Nelssen, S. S. Dritz, K. Q. Owen, J.C. Woodworth, and R. C. Sulabo. 2013b. Interactive effects of dietary ractopamine HCl and L-carnitine on finishing pigs: II. Carcass characteristics and meat quality. Journal of Animal Science. 91:3272–3282. doi:10.2527/jas.2011-4287

James, B. W., M. D. Tokach, R. D. Goodband, J. L. Nelssen, S. S. Dritz, K. Q. Owen, J.C. Woodworth, and R. C. Sulabo. 2013c. Effects of dietary L-carnitine and ractopamine HCl on the metabolic response to handling in finishing pig. Journal of Animal Science. 91:4426-4439. doi:10.2527/jas2011-4411

Jard, G., T. Liboz, F. Mathieu, A. Guyonvarc'h, and A. Lebrihi. 2011. Review of mycotoxin reduction in food and feed: from prevention in the field to detoxification by adsorption or transformation. Food Additives and Contaminants - Part A: Chemistry, Analysis, Control, Exposure & Risk Assessment. 28:1590-1609. doi:10.1080/19440049.2011.595377

Jiang, S. Z., Z. B. Yang, W. R. Yang, S. J. Wang, F. X. Liu, L. A. Johnston, F. Chi, and Y. Wang. 2012. Effect of purified zearalenone with or without modified montmorillonite on nutrient availability, genital organs and serum hormones in post-weaning piglets. Livestock Science. 144:110-118. doi:10.1016/j.livsci.2011.11.004

Jiang, Z. Y., W. J. Zhong, C. T. Zheng, Y. C. Lin, L. Yang, and S. Q. Jiang. 2010. Conjugated linoleic acid differentially regulates fat deposition in backfat and longissimus muscle of finishing pigs. Journal of Animal Science. 88:1694–1705. doi:10.2527/jas.2008-1551

Jondreville, C., P. S. Revy, and J. Y. Dourmad. 2003. Dietary means to better control the environmental impact of copper and zinc by pigs from weaning to slaughter. Livestock Production Science. 84:147-156. doi:10.1016/j.livprodsci.2003.09.011

Jones, C. K., J. R. Bergstrom, M. D. Tokach, J. M. DeRouchey, R. D. Goodband, J. L. Nelssen, and S. S. Dritz. 2010. Efficacy of commercial enzymes in diets containing various concentrations and sources of dried distillers grains with solubles for nursery pigs. Journal of Animal Science. 88:2084-2091. doi:10.2527/jas.2009-2109

Jouany, J. P. 2007. Methods for preventing, decontaminating and minimizing the toxicity of mycotoxins in feeds. Animal Feed Science and Technology. 137:342–362. doi:10.1016/j.anifeedsci.2007.06.009

Keegan, T. P., S. S. Dritz, J. L. Nelssen, J. M. DeRouchey, M. D. Tokach, and R. D. Goodband. 2005. Effects of in-feed antimicrobial alternatives and antimicrobials on nursery pig performance and weight variation. Journal of Swine Health and Production. 13:12-18.

Kerr, B. J., T. A. Kellner, and G. C. Shurson. 2015. Characteristics of lipids and their feeding value in swine diets. Journal of Animal Science and Biotechnology. 6:30–53. doi:10.1186/s40104-015-0028-x.

Kerr, B. J., T. E. Weber, and G. C. Shurson. 2013. Evaluation of commercially available enzymes, probiotics, or yeast on apparent total-tract nutrient digestion and growth in nursery and finishing pigs fed diets containing corn dried distillers grains with solubles. The Professional Animal Scientist. 29:508–517. doi: 10.15232/S1080-7446(15)30272-2

Kiarie, E., C. M. Nyachoti, B. A. Slominski, and G. Blank. 2007. Growth performance, gastrointestinal microbial activity, and nutrient digestibility in early-weaned pigs fed diets containing flaxseed and carbohydrase enzyme. Journal of Animal Science. 85:2982-2993. doi:10.2527/jas.2006-481.

Kiarie, E., S. Bhandari, M. Scott, D. O. Krause, and C. M. Nyachoti. 2011. Growth performance and gastrointestinal microbial ecology responses of piglets receiving *Saccharomyces cerevisiae* fermentation products after an oral challenge with *Escherichia coli* (K88). Journal of Animal Science. 89:1062-1078. doi:10.2527/jas.2010-3424

Kil, D. Y., Kwon, W. B., and Kim, B. G. 2011. Dietary acidifiers in weanling pig diets: a review. Revista Colombiana de Ciencias Pecuarias. 24:231-247.

Kim, B. G., M. D. Lindemann, and G. L. Cromwell. 2009. The effects of dietary chromium(III) picolinate on growth performance, blood measurements, and respiratory rate in pigs kept in high and low ambient temperature. Journal of Animal Science. 87:1695–1704. doi:10.2527/jas.2008-1218

Kiros, T. G., H. Derakhshani, E. Pinloche, R. D'Inca, Jason Marshall, E. Auclair, E. Khafipour, and A. Van Kessel. 2018. Effect of live yeast *Saccharomyces cerevisiae* (Actisaf Sc 47) supplementation on the performance and hindgut microbiota composition of weanling pigs. Scientific Reports. 8:5315-5328. doi:10.1038/s41598-018-23373-8

Kluge, H., J. Broz, and K. Eder. 2010. Effects of dietary benzoic acid on urinary pH and nutrient digestibility in lactating sows. Livestock Science. 134:119-121. doi:10.1016/j.livsci.2010.06.116

Kogan, G., and A. Kocher. 2007. Role of yeast cell wall polysaccharides in pig nutrition and health protection. Livestock Science. 109:161-165. doi:10.1016/j.livsci.2007.01.134

Larsen, S. T., B. R. Wiegand, F. C. Parrish, J. E. Swan, and J. C. Sparks. 2009. Dietary conjugated linoleic acid changes belly and bacon quality from pigs fed varied lipid sources. Journal of Animal Science. 87:285–295. doi:10.2527/jas.2008-1213

Liao, S. F., and M. Nyachoti. 2017. Using probiotics to improve swine gut health and nutrient utilization. Animal Nutrition. 3:331-343. doi:10.1016/j.aninu.2017.06.007

Lien, T.-F., C.-P. Wu, B.-J. Wang, M.-S. Shiao, T.-Y. Shiao, B.-H. Lin, J.-J. Lu, and C.-Y. Hu. 2001. Effect of supplemental levels of

chromium picolinate on the growth performance, serum traits, carcass characteristics and lipid metabolism of growing-finishing pigs. Animal Science. 72:289–296. doi:10.1017/S1357729800055788

Lindemann, M. D., C. M. Wood, A. F. Harper, E. T. Kornegay, and R. A. Anderson. 1995. Dietary chromium picolinate additions improve gain:feed and carcass characteristics in growing-finishing pigs and increase litter size in reproducing sows. Journal of Animal Science. 73:457–465. doi:10.2527/1995.732457x

Lindemann, M. D., S. D. Carter, L. I. Chiba, C. R. Dove, F. M. LeMieux, and L. L. Southern. 2004. A regional evaluation of chromium tripicolinate supplementation of diets fed to reproducing sows. Journal of Animal Science. 82:2972-2977. doi:10.2527/2004.82102972x

Liu, Y. 2015. Fatty acids, inflammation and intestinal health in pigs. Journal of Animal Science and Biotechnology. 6:41-50. doi:10.1186/s40104-015-0040-1

Liu, Y., C. D. Espinosa, J. J. Abelilla, G. A. Casas, L. V. Lagos, S. A. Lee, W. B. Kwon, J. K. Mathai, D. M. D. L. Navarro, N. W. Jaworski, and H. H. Stein. 2018. Non-antibiotic feed additives in diets for pigs: A review. Animal Nutrition. 4:113-125. doi:10.1016/j.aninu.2018.01.007

Lu, T., A. F. Harper, J. Zhao, M. J. Estienne, and R. A. Dalloul. 2014. Supplementing antioxidants to pigs fed diets high in oxidants: I. Effects on growth performance, liver function, and oxidative status. Journal of Animal Science. 92:5455–5463. doi:10.2527/jas.2013-7109

Maeda, K., K. Kohira, H. Kubota, K. Yamanaka, K. Saito, and M. Irie. 2017. Effect of dietary kapok oil supplementation on growth performance, carcass traits, meat quality and sensory traits of pork in finishing-pigs. Animal Science Journal. 88:1066-1074. doi:10.1111/asj.12731.

Marchant-Forde, J. N., D. C. Lay, E. A. Pajor, B. T. Richert, and A. P. Schinckel. 2003. The effects of ractopamine on the behavior and physiology of finishing pigs. Journal of Animal Science. 81:416–422. doi:10.2527/2003.812416x

Matthews, J. O., A. C. Guzik, F. M. Lemieux, L. L. Southern, and T. D. Bidner. 2005. Effects of chromium propionate on growth, carcass traits, and pork quality of growing-finishing pigs. Journal of Animal Science. 83:858–862. doi:10.2527/2005.834858x

Matthews, J. O., L. L. Southern, A. D. Higbie, M. A. Persica, and T. D. Bidner. 2001a. Effects of betaine on growth, carcass characteristics, pork quality, and plasma metabolites of finishing pigs. Journal of Animal Science. 79:722–728. doi:10.2527/2001.793722x

Matthews, J. O., L. L. Southern, T. D. Bidner, and M. A. Persica. 2001b. Effects of betaine, pen space, and slaughter handling method on growth performance, carcass traits, and pork quality of finishing barrows. Journal of Animal Science. 79:967–974. doi:10.2527/2001.794967x

Mendoza, S. M., R. D. Boyd, C. E. Zier-Rush, P. R. Ferket, K. D. Haydon, and E. van Heugten. 2017a. Effect of natural betaine and ractopamine HCl on whole-body and carcass growth in pigs housed under high ambient temperatures. Journal of Animal Science. 95:3047–3056. doi:10.2527/jas.2017.1622

Mendoza, S. M., R. D. Boyd, P. R. Ferket, and E. van Heugten. 2017b. Effects of dietary supplementation of the osmolyte betaine on growing pig performance and serological and hematological indices during thermoneutral and heat-stressed conditions. Journal of Animal Science. 95:5040–5053. doi:10.2527/jas2017.1905

Mersmann, H. J. 1998. Overview of the effects of β-adrenergic receptor agonists on animal growth including mechanisms of action. Journal of Animal Science. 76:160–172. doi:10.2527/1998.761160x

Mooney, K. W., and G. L. Cromwell. 1999. Efficacy of chromium picolinate on performance and tissue accretion in pigs with different lean gain potential. Journal of Animal Science. 77:1188-1198. doi:10.2527/1999.7751188x

Müller, H. L., M. Kirchgessner, F. X. Roth, and G. I. Stangl. 2000. Effect of conjugated linoleic acid on energy metabolism in growing-finishing pigs. Journal of Animal Physiology and Animal Nutrition. 83:85-94. doi:10.1046/j.1439-0396.2000.00253.x

Musser, R. E., R. D. Goodband, M. D. Tokach, K. Q. Owen, J. L. Nelssen, S. A. Blum, S. S. Dritz, and C. A. Civis. 1999. Effects of L-carnitine fed during gestation and lactation on sow and litter performance. Journal of Animal Science. 77:3289–3295. doi:10.2527/1999.77123289x

National Research Council. 2012. Nutrient Requirements of Swine. 11th Revised Edition. The National Academies Press, Washington, DC. doi:10.17226/13298

Owen, K. Q., H. Ji, C. V. Maxwell, J. L. Nelssen, R. D. Goodband, M. D. Tokach, G. C. Tremblay, and S. I. Koo. 2001b. Dietary L-carnitine suppresses mitochondrial branched-chain keto acid dehydrogenase activity and enhances protein accretion and carcass characteristics of swine. Journal of Animal Science. 79:3104–3112.

Owen, K. Q., J. L. Nelssen, R. D. Goodband, M. D. Tokach, and K. G. Friesen. 2001a. Effect of dietary L-carnitine on growth performance and body composition in nursery and growing-finishing pigs. Journal of Animal Science. 79:1509–1515.

Pérez, V. G., A. M. Waguespack, T. D. Bidner, L. L. Southern, T. M. Fakler, T. L. Ward, M. Steidinger, and J. E. Pettigrew. 2011. Additivity of effects from dietary copper and zinc on growth performance and fecal microbiota of pigs after weaning. Journal of Animal Science. 89:414–425. doi:10.2527/jas.2010-2839

Pietruszka, A., E. Jacyno, A. Kolodziej, M. Kawecka, C. Elzanowski, and B. Matysiak. 2009. Effects of L-carnitine and iron diet supplementations on growth performance, carcass characteristics, and blood metabolites in fattening pigs. Agricultural and Food Science. 18:27–34. doi:10.2137/145960609788066816

Ramanau, A., H. Kluge, J. Spilke, and K. Eder. 2004. Supplementation of sows with L-carnitine during pregnancy and lactation improves growth of the piglets during the suckling period through increased milk production. Journal of Nutrition. 134:86–92. doi:10.1093/jn/134.1.86

Ramanau, A., H. Kluge, J. Spilke, and K. Eder. 2008. Effects of dietary supplementation of L-carnitine on the reproductive performance of sows in production stocks. Livestock Science. 113:34–42. doi:10.1016/j.livsci.2007.02.009

Ramis, G., J. N. B. Evangelista, J. J. Quereda, F. J. Pallarés, J. M. De la Fuente, and A. Muñoz. 2011. Use of betaine in gilts and sows during lactation: effects on milk quality, reproductive

parameters, and piglet performance. Journal of Swine Health and Production. 19:226-232.

Real, D. E., J. L. Nelssen, M. D. Tokach, R. D. Goodband, S. S. Dritz, J. C. Woodworth, and K. Q. Owen. 2008. Additive effects of L-carnitine and chromium picolinate on sow reproductive performance. Livestock Science. 116:63-69. doi:10.1016/j.livsci.2007.08.009

Ritter, M. J., A. K. Johnson, M. E. Benjamin, S. N. Carr, M. Ellis, L. Faucitano, T. Grandin, J. L. Salak-Johnson, D. U. Thomson, C. Goldhawk, and M. S. Calvo-Lorenzo. 2017. Review: Effects of Ractopamine Hydrochloride (Paylean) on welfare indicators for market weight pigs. Translational Animal Science. 1:533–558. doi:10.2527/tas2017.0060

Rodrigues, I. and K. Naehrer. 2012. A three-year survey on the worldwide occurrence of mycotoxins in feedstuffs and feed. Toxins. 4:663–675. doi:10.3390/toxins4090663

Sales, J. 2011. A meta-analysis of the effects of dietary betaine supplementation on finishing performance and carcass characteristics of pigs. Animal Feed Science and Technology. 165:68–78. doi:10.1016/j.anifeedsci.2011.02.008

Sales, J., and F. Jančík. 2011. Effects of dietary chromium supplementation on performance, carcass characteristics, and meat quality of growing-finishing swine: A meta-analysis. Journal of Animal Science. 89:4054–4067. doi:10.2527/jas.2010-3495

Schrama, J. W., M. J. W. Heetkamp, P. H. Simmins, and W. J. J. Gerrits. 2003. Dietary betaine supplementation affects energy metabolism of pigs. Journal of Animal Science. 81:1202–1209. doi:10.2527/2003.8151202x

Shawk, D. J., S. S. Dritz, R. D. Goodband, M. D. Tokach, J. C. Woodworth, and J. M. DeRouchey. 2018. Effects of sodium metabisulfite additives on nursery pig growth. Translational Animal Science. txy098. doi:10.1093/tas/txy098

Shelton, J. L., R. L. Payne, S. L. Johnston, T. D. Bidner, L. L. Southern, R. L. Odgaard, and T. G. Page. 2003. Effect of chromium propionate on growth, carcass traits, pork quality, and plasma metabolites in growing-finishing pigs. Journal of Animal Science. 81:2515–2524. doi:10.2527/2003.81102515x

Shelton, N. W., M. D. Tokach, J. L. Nelssen, R. D. Goodband, S. S. Dritz, J. M. DeRouchey, and G. M. Hill. 2011. Effects of copper sulfate, tri-basic copper chloride, and zinc oxide on weanling pig performance. Journal of Animal Science. 89:2440–2451. doi:10.2527/jas.2010-3432

Shen, Y. B., X. S. Piao, S. W. Kim, L. Wang, P. Liu, I. Yoon, and Y. G. Zhen. 2009. Effects of yeast culture supplementation on growth performance, intestinal health, and immune response of nursery pigs. Journal of Animal Science. 87:2614-2624. doi:10.2527/jas.2008-1512.

Shurson, G. C., B. J. Kerr, and A. R. Hanson. 2015. Evaluating the quality of feed fats and oils and their effects on pig growth performance. Journal of Animal Science and Biotechnology. 6:10–21. doi:10.1186/s40104-015-0005-4

Song, R., C. Chen, L. J. Johnston, B. J. Kerr, T. E. Weber, and G. C. Shurson. 2014. Effects of feeding diets containing highly peroxidized distillers dried grains with solubles and increasing vitamin E levels to wean-finish on growth performance, carcass characteristics, and pork fat composition. Journal of Animal Science. 92:198–210. doi:10.2527/jas.2013-6334

Soto, J. A., M. D. Tokach, S. S. Dritz, J. C. Woodworth, J. M. DeRouchey, and B. D. Goodband. 2018. Evaluation of dietary phytogenics on growth performance and carcass characteristics of pigs during the growing-finishing phase. Journal of Animal Science. 96(Suppl. 2):125–126. doi:10.1093/jas/sky073.232

Stahly, T. S., G. L. Cromwell, and H. J. Monegue.1980. Effect of single additions and combinations of copper and antibiotics on the performance of weanling pigs. Journal of Animal Science. 51:1347–1351.

Stein, H. H., and D. Y. Kil. 2006. Reduced use of antibiotic growth promoters in diets fed to weanling pigs: Dietary tools, part 2. Animal Biotechnology.17:217-231. doi:10.1080/10495390600957191

Suiryanrayna, M. V., and J. V. Ramana. 2015. A review of the effects of dietary organic acids fed to swine. Journal of Animal Science and Biotechnology. 6:45-55. doi:10.1186/s40104-015-0042-z

Thacker, P. A. 2013. Alternatives to antibiotics as growth promoters for use in swine production: A review. Journal of Animal Science and Biotechnology. 4:35-47. doi:10.1186/2049-1891-4-35

Thiel-Cooper, R. L., F. C. Parrish, J. C. Sparks, B. R. Wiegand, and R. C. Ewan. 2001. Conjugated linoleic acid changes swine performance and carcass composition. Journal of Animal Science. 79:1821–1828.

Torres-Pitarch, A., D. Hermans, E. G. Manzanilla, J. Bindelle, N. Everaert, Y. Beckers, D. Torrallardona, G. Bruggeman, G. E. Gardiner, and P. G. Lawlor. 2017. Animal Feed Science and Technology. 233:145-159. doi:10.1016/j.anifeedsci.2017.04.024

Tran, T. H. T., N. Everaert, and J. Bindelle. 2016. Review on the effects of potential prebiotics on controlling intestinal enteropathogens Salmonella and Escherichia coli in pig production. Journal of Animal Physiology and Animal Nutrition. 102:17-32. doi:10.1111/jpn.12666

Tung, C., and J. Pettigrew. 2006. Critical review of acidifiers. National Pork Board. #05-169. Available at: http://old.pork.org/filelibrary/animalscience/reviewofacidifiers.pdf

Upadhaya, S., K. Lee, and I. Kim. 2014. Protected organic acids blends as an alternative to antibiotics in finishing pigs. Asian-Australasian Journal of Animal Science. 27:1600-1607. doi:10.5713/ajas.2014.14356

van der Aar, P. J., F. Molist, and J. D. van der Klis. 2017. The central role of intestinal health on the effect of feed additives on feed intake in swine and poultry. Animal Feed Science and Technology. 233:64-75. doi:10.1016/j.anifeedsci.2016.07.019

van Wettere, W. H. E. J., P. Herde, and P. E. Hughes. 2012. Supplementing sow gestation diets with betaine during summer increases litter size of sows with greater numbers of parities. Animal Reproduction Science. 132:44-49. doi:10.1016/j.anireprosci.2012.04.007

van Wettere, W. H. E. J., R. J. Smits, and P. E. Hughes. 2013. Methyl donor supplementation of gestating sow diets improves pregnancy outcomes and litter size. Animal Production Science. 53:1–7. doi:10.1071/AN11350

Vila-Donat, P., S. Marín, V. Sanchis, and A. J. Ramos. 2018. A review of the mycotoxin adsorbing agents, with an emphasis on their multi-binding capacity, for animal feed

decontamination. Food and Chemical Toxicology. 114:246-259. doi:10.1016/j.fct.2018.02.044

Walk, C. L., P. Wilcock, and E. Magowan. 2015. Evaluation of the effects of pharmacological zinc oxide and phosphorus source on weaned piglet growth performance, plasma minerals and mineral digestibility. Animal. 9:1145-1152. doi:10.1017/S175173111500035X

Wang, L., Z. Shi, Z. Jia, B. Su, B. Shi, and A. Shan. 2013. The effects of dietary supplementation with chromium picolinate throughout gestation on productive performance, Cr concentration, serum parameters, and colostrum composition in sows. Biological Trace Element Research. 154:55-61. doi:10.1007/s12011-013-9699-3

Wei, B., Q. Meng, S. He, Z. Qu, S. Nie, B. Shi, and A. Shan. 2018. Effects of L-carnitine in the distillers dried grains with solubles diet of sows on reproductive performance and antioxidant status of sows and their offspring. Animal. 1-10. doi:10.1017/S1751731118003105

White, H. M., B. T. Richert, J. S. Radcliffe, A. P. Schinckel, J. R. Burgess, S. L. Koser, S. S. Donkin, and M. A. Latour. 2009. Feeding conjugated linoleic acid partially recovers carcass quality in pigs fed dried corn distillers grains with solubles, Journal of Animal Science. 87:157–166. doi:10.2527/jas.2007-0734

Whitley, N. C., M. Thomas, J. L. Ramirez, A. B. Moore, and N. M. Cox. 2002. Influences of parity and level of feed intake on reproductive response to insulin administration after weaning in sows. Journal of Animal Science. 80:1038–1043.

Windisch, W., K. Schedle, C. Plitzner, and A. Kroismayr. 2008. Use of phytogenic products as feed additives for swine and poultry. Journal of Animal Science. 86:140-148. doi:10.2527/jas.2007-0459

Woodworth, J. C., M. D. Tokach, J. L. Nelssen, R. D. Goodband, S. S. Dritz, S. I. Koo, J. E. Minton, and K. Q. Owen. 2007. Influence of dietary L-carnitine and chromium picolinate on blood hormones and metabolites of gestating sows fed one meal per day. Journal of Animal Science. 85:2524–2537. doi:10.2527/jas.2006-284

Yazdankhah, S., K. Rudi, and A. Bernhoft. 2014. Zinc and copper in animal feed – development of resistance and co-resistance to antimicrobial agents in bacteria of animal origin. Microbial Ecology in Health and Disease. 25:25862-25869. doi:10.3402/mehd.v25.25862.

Ying, W., M. D. Tokach, J. M. DeRouchey, T. E. Houser, S. S. Dritz, R. D. Goodband, and J. L. Nelssen. 2013. Effects of dietary L-carnitine and dried distillers grains with solubles on growth, carcass characteristics, and loin and fat quality of growing-finishing pigs. Journal of Animal Science. 91:3211–3219. doi:10.2527/jas.2012-5606

Yoder, A., M. D. Tokach, J. M. DeRouchey, C. B. Paulk, C. R. Stark, and C. K. Jones. 2017. Cleaning reduces mycotoxin contamination in corn. Kansas Agricultural Experiment Station Research Reports. 3:7. doi:10.4148/ 2378-5977.7503

Young, J. C., H. L. Trenholm, D. W. Friend, and D. B. Prelusky. 1987. Detoxification of deoxynivalenol with sodium bisulfite and evaluation of the effects when pure mycotoxin or contaminated corn was treated and given to pigs. Journal of Agricultural and Food Chemistry. 35:259–261. doi:10.1021/jf00074a023

Yu, X. H., R. Rawat, and J. Shanklin. 2011. Characterization and analysis of the cotton cyclopropane fatty acid synthase family and their contribution to cyclopropane fatty acid synthesis. BMC Plant Biology. 11:97-107. doi:10.1186/1471-2229-11-97-107.

Zeng, Z., S. Zhang, H. Wang, and X. Piao. 2015. Essential oil and aromatic plants as feed additives in non-ruminant nutrition: a review. Journal of Animal Science and Biotechnology. 6:7-17. doi:10.1186/s40104-015-0004-5

Zentek Z., S. Buchheit-Renko, F. Ferrara, W. Vahjen, A. G. Van Kessel, and R. Pieper. 2011. Nutritional and physiological role of medium-chain triglycerides and medium-chain fatty acids in piglets. Animal Health Research Reviews. 12:83-93. doi:10.1017/S1466252311000089

Zhang, S., M. Tian, H. Song, K. Shi, Y. Wang, and W. Guan. 2018. Effects of L-carnitine on reproductive performance, milk composition, placental development and IGF concentrations in blood plasma and placental chorions in sows. Archives of Animal Nutrition. doi:10.1080/1745039X.2018.1471185

Zhu, C., H. Lv, Z. Chen, K. Wang, X. Wu, Z. Chen, W. Zhang, R. Liang, and Z. Jiang. 2017. Dietary zinc oxide modulates antioxidant capacity, small intestinal development, and jejunal gene expression in weaned pigs. Biological Trace Element Research. 175:331-338. doi:10.1007/s12011-016-0767-3

Zier-Rush, C.E., C. Groom, M. Tillman, J. Remus, and R.D. Boyd. 2016. The feed enzyme xylanase improves finish pig viability and carcass feed efficiency. Journal of Animal Science. 94(Suppl. 2):115. doi:10.2527/msasas2016-244.

Zimmermann, J. A., M. L. Fusari, E. Rossler, J. E. Blajman, A. Romero-Scharpen, D. M. Astesana, C. R. Olivero, A. P. Berisvil, M. L. Signorini, M. V. Zbrun, L. S. Frizzo, and L. P. Soto. 2016. Effects of probiotics in swines growth performance: a meta- analysis of randomized controlled trials. Animal Feed Science and Technology. 219:280-293. doi:10.1016/j.anifeedsci.2016.06.021

Zuo, J., B. Ling, L. Long, T. Li, L. Lahaye, C. Yang, and D. Feng. 2015. Effect of dietary supplementation with protease on growth performance, nutrient digestibility, intestinal morphology, digestive enzymes and gene expression of weaned piglets. Animal Nutrition. 1:276-282. doi:10.1016/j.aninu.2015.10.003