Diet acidification and the merits of benzoic acid for swine nutrition and sustainable pork production
Jon Bergstrom, Ph.D., DSM Animal Nutrition and Health

Introduction
The acidification of animal feed is a preventative control that can be applied in formulation to reduce the diet pH and minimize the risk of contamination with bacteria that may cause foodborne illness in humans or animals (U.S. FDA, 2018). However, the risk for foodborne illness from livestock feeds is frequently poorly understood. Also, the differences among the acids that are available for use in animal feeds are seldom clear to nutritionists and producers, and an incomplete understanding of their use and benefits (relative to costs) has generally resulted in there being limited attention given to the use of acids as a preventative control in feeds.

Historically, feed-grade antibiotics have frequently been used to prevent all types of diseases and improve growth performance in food animals. Despite the growth-promoting and economic benefits realized from feed-grade antibiotics, their use is substantially declining in the U.S. (and globally) for several reasons:
1) dutiful concerns for limiting the development of antimicrobial resistance to medically important antibiotics
2) changing regulations
3) increasing consumer demand for products from animals raised without antibiotics

The declining use of antibiotics in the production of food animals is especially evident when the trends for reduced overall usage are considered collectively with the increasing volumes of animal products that are being produced (U.S. FDA, 2019a; U.S. FDA, 2019b; National Pork Board, 2019). Nevertheless, the judicious use of antibiotics (on a case-by-case basis) is necessary for veterinarian-client relationships because there is a responsibility to prevent, treat, or control pathogens that affect the welfare of animals and the public health (Stanton, 2013).

With increased restrictions on using feed-grade antibiotics for growth promotion, however, there is growing interest in identifying alternatives for improving the growth and efficiency of food-producing animals and the sustainability of animal productivity. The growth-promoting benefits of feed-grade antibiotics are primarily attributed to their ability to regulate the risk for digestive upset, although the exact mechanisms have not entirely been elucidated (Allen et al., 2013; Heo et al., 2013). Importantly, not all cases of digestive upset that result in clinical diarrhea are caused by pathogens (Hoogland, 2012).
Generally, the subtherapeutic levels of feed-grade antibiotics capable of eliciting improvements in growth performance are less than the therapeutic levels necessary to treat disease. Over time, subtherapeutic levels of antibiotics may contribute to the evolution of resistant bacteria and increased difficulties for treating future diseases (Allen et al., 2013).

Alternatives to feed-grade antibiotics for growth promotion should demonstrate an ability to reduce the risk for digestive upset and sustain the productive efficiency of the target animals (Heo et al., 2013). However, a long-term and societal value for using alternatives that help reduce antibiotic usage and the risks of pathogen resistance to medically important antibiotics also needs to be considered.

Increased knowledge and research are improving the possibilities for successful pork production without feed-grade antibiotics (Thacker, 2013). Improvements in growth and productive efficiency are continuing with developments in genetics, nutrition, health, and management. Biosecurity plans for modern farms have continued to evolve for improved disease prevention. Recently, there’s been an increase in awareness of the potential for pathogens, including viruses, to contaminate feed or feed ingredients and transmit disease (Stewart et al., 2020; USDA, 2019). Currently, feed preservatives and acidification agents are recognized by the FDA as preventative controls in formulation that can be used to mitigate the risks associated with microbial growth and pathogens in feed (U.S. FDA, 2018). Nutritionally, feed additives, such as phytases and other exogenous feed enzymes, are increasingly being used to improve the digestibility of plant-based feed ingredients and more sustainably meet the nutritional requirements of modern pigs.

Other feed additives, including inorganic and organic acids, essential oils, probiotics, and prebiotics, have also been proven helpful in nutritional programs (Heo et al., 2013). Of these, the use of organic acids is currently among the most common in pig feeds, especially in diets fed immediately post-weaning (Suiryanrayna and Ramana, 2015).

**Diet acidification in swine nutrition**

During the last forty years, there has been increased interest in adding acids to pig diets, and acidification has especially been beneficial for diets fed post-weaning (Tung and Pettigrew, 2006). This is primarily because natural acidification of the stomach from HCl secretion is less developed in young, suckling pigs. Suckling pigs have an immature digestive tract and maintain functional gastric acidity via the microbial fermentation of milk lactose to lactic acids (Cranwell et al., 1976). When pigs are abruptly weaned from milk to solid diets, there is a rather sudden microbial imbalance with transient changes to gastrointestinal morphology that impair nutrient utilization and reduce energy metabolism (Li et al., 2018). When care is not taken to try and maintain a normal, beneficial gastric pH, there may be increased susceptibility to enteric infections (Heo et al., 2013). During such a stressful period, the dietary addition of some organic acids has helped sustain digestive health, reduce the lag in growth from abrupt weaning, and improve growth performance (Pettigrew, 2006). The benefits of dietary organic acids have commonly occurred in starter diets already containing growth-promoting antibiotics (Bergstrom et al., 1994 and 1996). However, the measured benefits of dietary organic acids have generally not been as consistent or remarkable when compared to feeding growth-promoting antibiotics alone (Walsh et al., 2007; Partanen and Mroz, 1999). Advantages with diet acidification are seldom the same as those from feed-grade antibiotics, and their benefits should be considered independent from one another. Our understanding of swine feed acidification programs has improved, while the use of feed-grade antibiotics has diminished.

The variation in the responses to diet acidification in the peer-reviewed literature has been attributed to the various acids and levels used, the composition of the basal diet, the weight and/or age of the pigs, and the existing conditions or level of performance (Liu et al., 2018; Suiryanrayna and Ramana, 2015; Tung and Pettigrew, 2006). In practical terms, inorganic acids are very caustic and possess few desirable characteristics as acidifiers for manufactured swine feeds. Phosphoric acid is sometimes used at low levels in blended combinations with organic acids, but organic acids are the most practical and frequently used for acidification of swine diets. The most frequently used and researched organic acids have been formic acid, fumaric acid, propionic acid, lactic acid, and citric acid, with lesser interest in acetic acid, malic acid and sorbic acid, but increasing interest in pure benzoic acid and butyric acid (FEFANA Working Group Organic Acids, 2014; Partanen et al., 2009; Tung and Pettigrew, 2006; Partanen and Mroz, 1999).
Differences among the individual acids

Benefits from diet acidification vary, and include feed preservation from reduced diet pH and inhibited microbial growth, decreased or stabilized gastric pH for sustained pepsin activity and digestion, improved intestinal mucosal cell development and a more favorable gut microbiome, and improved nutrient digestibility and retention (FEFANA Working Group Organic Acids, 2014). Because the physicochemical properties and metabolism for each of the acids vary, none of the individual acids have demonstrated all the suggested benefits (Partanen, 2001). In fact, in a critical analysis of peer-reviewed research, including a few blends or combinations of acids, Tung and Pettigrew (2006) reported that acidifiers effectively reduced the pH of the diets but did not affect the pH in the gastrointestinal tract or digesta. They also reported that acidifiers affected the digestive microbial populations inconsistently when considering the Lactobacillus/Bifidobacterium and E. coli populations in various sections of the gastrointestinal tract. Nevertheless, acidifiers generally improved the digestibility of dry matter (DM) and crude protein (CP), as well as the ADG of pigs, especially during the first two weeks after weaning.

In an earlier review of dietary organic acids for pigs, Partanen and Mroz (1999) suggested that changes in ADG and F/G in nursery-aged pigs could be modeled based on the specific acid, the dietary acid level, feed intake, and acid × feed intake interactions. Therefore, the effects of some acids may depend on their ability to affect post-weaning feed intake. As in the review by Tung and Pettigrew (2006), most of their peer-reviewed research was with formic, fumaric, and citric acids, and included acid levels ranging from 0.35% to 3%. While lower levels of formic acid or formates in the diet may not affect feed intake, levels exceeding 1% can reduce feed intake and growth (Partanen et al., 2009; Partanen, 2001; Eckel et al., 1992; Eidelsburger et al., 1992; Grassmann et al., 1992). Reductions in feed intake may occur because pigs are limited in their ability to metabolize formate, and the accumulation of formate in blood can cause acidosis and ocular toxicity (Makar et al., 1990); whereas citric, fumaric, and lactic acids are absorbed and normally metabolized via the citric acid cycle, with butyrate readily used as an energy source by enterocytes. Despite the evidence showing that diet acidification can improve post-weaning pig performance, it’s been difficult to identify optimal dietary levels because the number of dose-response studies has been limited (Partanen, 2001).

While there is little research to describe the acceptability of consuming acidified diets, there is evidence that weanling pigs may prefer a non-acidified diet over a diet containing either (3%) citric or (1.5%) fumaric acid (Henry et al., 1985). Citric acid or fumaric acid has generally not resulted in changes of post-weaning ADFI; and increases in ADG with these acids have largely been associated with an improved F/G (Kil et al., 2011; Partanen, 2001; Partanen and Mroz, 1999). Feeding diets containing lactic acid has been reported to enhance post-weaning feed intake. Diets containing a reasonable level of formic acid have been shown to be as acceptable to pigs as lactic acid, but formic acid has been found to be less preferable to pigs when compared to a diet containing sodium benzoate (Partanen, 2002; Roth et al., 1993). Sodium benzoate was the first food preservative to be approved by the U.S. Food and Drug Administration and is still a very common preservative today; however, it is limited to a 0.1% inclusion as a preservative and is not approved at higher levels to acidify swine diets. Sodium butyrate has also been demonstrated to increase post-weaning ADFI, even when added to diets already containing other organic acids (Tsai et al., 2019; Lu et al., 2008; Piva et al., 2002). The major functions of butyrate occur in the lower intestine. A properly protected form of sodium butyrate is required to reduce any ineffectual absorption in the upper intestine, as well as to improve product acceptability and handling characteristics. As in the research with other acids, responses to butyrate in pig diets have been variable, and the potential benefits are mostly evident in the period immediately after weaning (Bedford and Gong, 2018).

Considerations for practical and effective diet acidification

Although several organic acids have been demonstrated to improve post-weaning pig performance, most of the commercially available acidifiers in North America are proprietary blends that have not been evaluated extensively with support in the peer-reviewed research. Some of the primary reasons for the predominance of commercial acidifier blends are noted below:

1) to combine certain acids with the desired physicochemical properties,
2) to reduce the total amount of acidification and cost,
3) to improve product characteristics and reduce safety and handling limitations, and
4) to differentiate and propose a competitive value.
Despite the limited amount of research with blends of acids, much of the available research has used dietary levels >1% and failed to show advantages over a single acid. The limited research with blends of acids at levels <1% has shown less consistent benefits for performance (Tung and Pettigrew, 2006; Kil et al., 2011). Nevertheless, many commercial acidifiers can be found with recommendations at dietary levels <1%.

Many of the pure organic acids that have been evaluated in the peer-reviewed research are liquid in form. Citric acid and fumaric acid exist in a dry, solid form, but other common organic acids are liquid (i.e., formic, lactic, propionic, and butyric). Concentrated liquid acids are generally the least acceptable for manufacturing feeds, primarily because they require more careful handling, specialized equipment, and are corrosive. The use of carriers and coating technologies attempts to accommodate safer and more convenient handling of the acids. However, the salt forms of organic acids (i.e., Ca-formate) are generally ineffective for reducing the pH and acid buffering capacity of the diet.

The potential benefit from diet acidification can depend upon the initial acid buffering capacity of the diet and the level of any acid(s) (Blank et al., 2001). High protein ingredients (both animal/milk- and vegetable-sourced) common to weaned-pig diets have a high acid buffering capacity, but inorganic sources of minerals, especially limestone or CaCO3, can greatly affect the acid buffering capacity of the diet (Lawlor et al., 2005). In fact, Radcliffe et al. (1998) observed that stomach pH increased as dietary CaCO3 was increased to maintain a constant total Ca to available P ratio with increased dietary phytase levels. Stomach pH was not different when phytase levels were increased with a fixed dietary level and ratio of total Ca and total P in their second experiment, but high levels of 1.5% to 3% added citric acid did reduce both the diet and stomach pH in either case. Gastric pH for weaned pigs can become compromised further if formulation efforts are only focused on meeting the energy and nutrient needs of pigs. Lipid coated acidifiers do not affect diet and stomach pH but are primarily intended to protect the activity of organic acids and provide benefit in the lower intestine (i.e., butyric acid; Bedford and Gong, 2018; Piva et al., 2007).

**Pure benzoic acid — the most novel and versatile organic acid for acidifying swine feeds**

Benzoic acid and benzoates are among the earliest and most common organic acids to be used as food or feed preservatives, generally because they have the broadest spectrum of activity against spoilage bacteria, fungi, and yeasts (Wedzicha, 2003). Sodium benzoate is “Generally Regarded As Safe” (GRAS) for use as a food preservative and feed additive at up to 0.1% (U.S. FDA, DHHS, "Foods and Drugs", 21 CFR § 582.3733; AAFCO, 2004, “Official Publication”: 262). More recently, on March 13, 2014, the United States Food and Drug Administration amended the regulations for food additives to permit the safe use of pure (≥99.5%) benzoic acid as an acidifying agent at up to 0.5% in swine feeds (U.S. FDA, DHHS, “Foods and Drugs”, 21 CFR § 573.210). Pure benzoic acid is also recognized as a safe additive for acidifying swine feeds by the European Food Safety Authority (EFSA), with effective dietary levels within the range of 0.3% to 1% (EFSA, 2019, 2015, 2007, and 2005; European Commission [EC], 2002). Since the year 2000, there is increasing evidence to demonstrate benzoic acid is well-suited for acidifying swine feeds (Table 1).
North American nursery-pig research

In some of the first studies to evaluate the effects of feeding 0.5% benzoic acid on nursery pig performance in the U.S., Nemechek et al., (2013abc) reported positive responses in some experiments but that there were no effects in others. There are several possible reasons for the inconsistent results. In studies with pigs at the university teaching and research herd, the level of performance observed for pigs fed the control diets was exceptional, even for those fed simple diets that contained more soybean meal, but no animal protein sources, lactose or high levels of zinc oxide. Although the pH and buffering capacity of the diets were not reported, all diets fed during the first 14 days contained greater than 20% crude protein and significant amounts of limestone and phosphate. Low levels of phytase were used in the diets, and the monocalcium phosphate and limestone were increased in the simple (vs. complex) diets to maintain similar dietary calcium and phosphorus levels. It’s possible that a high buffering capacity, as well as the exceptional level of post-weaning feed intake and performance, reduced the likelihood of obtaining improvements from diet acidification using 0.5% benzoic acid. Nevertheless, there were improvements in pig performance from feeding 0.5% benzoic acid when studies were conducted in a commercial research barn, especially in conditions where pigs began receiving the diets at a lighter BW and younger age with a lower level of feed intake and growth during the first weeks in the experiment.

Recent trials in North America have shown consistent improvements in post-weaning pig performance when 0.5% benzoic acid was used for feed acidification. Bradley et al. (2019) reported that ADG and ADFI were increased for pigs fed diets with benzoic acid from day 0 to 21 post-weaning, even when diets contained high levels of zinc oxide (Table 2). Feed conversion was also improved with 0.5% benzoic acid in diets with low ZnO. In another post-weaning study, Bergstrom et al. (2020) found that diets with 0.5% benzoic acid improved ADG and ending BW during days 0 to 13 and 13 to 20 post-weaning. Feed efficiency was also improved from day 0 to 13, and there was a tendency for pigs fed diets containing any of the acids to have greater ADFI from day 13 to 20. Feeding either 0.25% benzoic acid or a commercialized blend product had no effect. In both studies, high levels of phytase were used in all diets to reduce the levels of inorganic Ca and P sources. Other considerations to attenuate the initial dietary buffering capacity were implemented in diet formulation. For example, crediting phytase for improved digestibility of amino acids and using optimal levels of synthetic amino acids to reduce excess crude protein was incorporated.

In the study by Bradley et al. (2019), a low (0.05%) level of a (51.5%) phosphoric acid was used with the 0.5% benzoic acid to further reduce dietary buffering potential. Thanh et al. (2018) reported an 11% increase in nursery pig ADG when 0.5% benzoic acid was added to a control diet with a low (0.1%) level of phosphoric acid. Furthermore, a source of sodium butyrate (0.1%) was also used with the 0.5% benzoic acid and low level of phosphoric acid in the study by Bradley et al. (2019). Previous work indicated that benzoic acid and sodium butyrate can provide additive benefits because their mechanisms are different (Tsai et al., 2019; Watson et al., 2020). Nevertheless, the potential for consistent benefits from feeding benzoic acid is increasingly evident from research.

Extensive research shows benzoic acid does more

The benefits of benzoic acid to acidify nursery swine feeds has been demonstrated in Europe, Asia, and Latin America since the year 2000. In Denmark, Maribo et al. (2000) reported that benzoic acid (2% in the first 2 weeks and 1% in the last 4 weeks) significantly reduced incidence of diarrhea in pigs. In addition, benzoic acid-fed pigs had a higher production value (based on weight gain, feed intake, and feed efficiency) when compared to pigs fed the control diet or a diet containing a combination of 0.7% formic acid and 0.7% lactic acid. In a subsequent...
experiment by Maribo (2003), nursery-aged pigs fed either 0.5% benzoic acid or a product containing plant extracts had a higher production value than those fed the control diet, but no differences existed in incidence of diarrhea. Pigs fed an oregano oil product with or without a combination of lactic acid, formic acid, and butyric acid did not perform differently from the control.

Numerous other studies demonstrating the positive effects of adding benzoic acid to nursery pig feeds have occurred since the publication of earlier reviews on diet acidification (Kil et al., 2011; Partanen et al., 2009, 2001, 1999; Tung and Pettigrew, 2006). In addition to the nursery period, benzoic acid can provide benefits during the growing and finishing phases (Kim et al., 2008). A number of studies have shown benzoic acid to improve ADG, BW, ADFI, and F/G (Chen et al., 2016; Diao et al., 2015; Gräber et al., 2012; Guggenbuhl et al., 2007; Gutzwiller et al., 2014; Halas et al., 2010; Kim et al., 2008; Kluge et al., 2005; Silveira et al., 2018; Torrallardona et al., 2007; Voth et al., 2018).

The benefits from benzoic acid in swine diets result from its acidification and its potential to help maintain multiple digestive mechanisms. Other acids, either used alone or in combination, have been less successful. With an awareness already established for the importance of diet pH and buffering capacity, particularly for young pigs, the addition of benzoic acid to pig feeds has reduced the pH of digesta in the stomach, jejunum, ileum, or caecum contents during the feeding period (Chen et al., 2016; Diao et al., 2015; Diao et al., 2014; Silveira et al., 2018). A lower pH of digesta in the distal small intestine from feeding benzoic acid is possible because it is not absorbed or metabolized the same as other organic acids (Kristensen et al., 2009). Although much of it can be absorbed in the proximal gastrointestinal tract, a portion of the ingested benzoic acid remains in the lumen of the distal small intestine (Maribo et al., 2000).

The ability for a portion of ingested benzoic acid to reach the distal small intestine may be responsible for differences found in the normal microbiota populations in the stomach, duodenum, jejunum, ileum, or caecum contents in pigs fed benzoic acid (Chen et al., 2016; Diao et al., 2014; Guggenbuhl et al., 2007; Kluge et al., 2005). Consequently, pigs fed benzoic acid often had less E. coli bacteria in these segments of the gastrointestinal tract. Knarreborg et al. (2002), while establishing an in vitro methodology to study effects of organic acids on the coliform and lactic acid bacteria in the proximal portion of the gastrointestinal tract, demonstrated that benzoic acid was superior for inhibiting coliform bacteria when compared to fumaric, lactic, propionic, butyric, and formic acids (Table 3).

Feeding benzoic acid has also been found to support normal morphology and development within the gastrointestinal tract of nursery-aged pigs. In several studies, feeding benzoic acid to pigs resulted in increased maturity of the epithelium in the duodenum, jejunum, and/or ileum, as indicated by measurements of villus height, crypt depth, or villus height-to-crypt depth ratio (Chen et al., 2016; Diao et al., 2015; Diao et al., 2014; Halas et al., 2010; Silveira et al., 2018). Feeding pigs benzoic acid has also been associated with increases in butyric acid in the caecum and colon, especially in grower pigs (Bühler et al., 2009; Silveira et al., 2018). Collectively, these effects help to understand the improvements in digestibility of N (or CP), energy, NDF, Ca, and P that have occurred when benzoic acid was included in the diets of nursery- or grower-aged pigs (Bühler et al., 2009; Diao et al., 2015; Guggenbuhl et al., 2007; Halas et al., 2010; Sauer et al., 2009).

The increased digestibility of N, Ca, and P for pigs fed a diet with benzoic acid is often associated with greater retention of these elements. Additionally, a reduction in total N excretion can result from significant reductions in the contribution of urinary N excretion with increasing levels of dietary benzoic acid, and this is associated with a reduction in urine pH. The reduction in urinary pH from feeding benzoic acid occurs because it is absorbed in the small intestine, metabolized in the liver to form hippuric acid, and an increased level of hippuric acid is excreted in the urine. The reductions in urinary N excretion and urine pH can result in significant reductions in the pH of the manure slurry and therefore reduce emissions of ammonia. (Gräber et al., 2012; Gutzwiller et al., 2014; Kluge et al., 2005; Kristensen et al., 2009; Murphy et al., 2011; Sauer et al., 2009).
Conclusions

Organic acids and diet acidification are among the most viable alternatives that are being considered to help maintain or improve the nutrition for pigs, both now and into the future. In the past, the benefits of diet acidification for swine have primarily occurred during the first weeks after weaning, but the results have not been consistent. Various acids have been used to acidify diets but understanding the differences among the acids and their more specific benefits has been difficult.

Pure benzoic acid is the most recent organic acid to receive interest and acceptance as an acidifier for swine feed. Unlike other acids, benzoic acid has shown more consistency in pig performance. Benzoic acid helps maintain performance with reduced dietary pH and improved digestive function. The versatility of benzoic acid in swine feeds has been demonstrated, and it’s been effective in diets containing phytogenic compounds or flavorings, enzymes, and even other acids (i.e., sodium butyrate). Up to 0.5% benzoic acid can improve pig performance while 1% permitted in the EU can be especially useful for achieving higher sustainability targets.

Table 1. Relative acidification characteristics of the various acids when included in swine feeds* (*“+” indicates beneficial effect, “-” indicates detrimental effect, and “0” indicates ineffectual).

<table>
<thead>
<tr>
<th>Acid</th>
<th>Diet pH effect</th>
<th>Effect on buffering</th>
<th>Action on bacteria</th>
<th>Action on yeasts</th>
<th>Action on molds</th>
<th>Palatability</th>
<th>Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzoic</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>0</td>
<td>0</td>
<td>- - -</td>
</tr>
<tr>
<td>Phosphoric</td>
<td>+++</td>
<td>+++</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>- - -</td>
</tr>
<tr>
<td>Butyric</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Citric</td>
<td>++</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Formic</td>
<td>+++++</td>
<td>+++++</td>
<td>+</td>
<td>++</td>
<td>0</td>
<td>-</td>
<td>- - -</td>
</tr>
<tr>
<td>Fumaric</td>
<td>+++</td>
<td>+++</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Lactic</td>
<td>++</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Propionic</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

*DSM technical review

Benzoic acid has positive impacts in all categories with no negative impact to palatability

Table 2. The effects of adding a combination of (0.5%) benzoic acid, (0.1%) coated sodium butyrate product, and (0.025%) phosphoric acid (OA) to nursery diets; either with or without high levels of zinc oxide (ZnO); on pig performance from day 0 to 21 post-weaning (Bradley et al., 2012):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Control + ZnO</th>
<th>Control + OA</th>
<th>Control + ZnO + OA</th>
<th>SEM</th>
<th>P=</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 0 to 21 Initial BW, kg</td>
<td>6.45</td>
<td>6.42</td>
<td>6.44</td>
<td>6.45</td>
<td>0.030</td>
<td>0.867</td>
</tr>
<tr>
<td>ADG, g</td>
<td>201a</td>
<td>245b</td>
<td>241b</td>
<td>285c</td>
<td>6.8</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>ADFI, g</td>
<td>273a</td>
<td>311b</td>
<td>299b</td>
<td>344c</td>
<td>6.4</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>F/G</td>
<td>1.39b</td>
<td>1.29b</td>
<td>1.25b</td>
<td>1.24b</td>
<td>0.022</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>D 21 BW, kg</td>
<td>10.73a</td>
<td>11.62b</td>
<td>11.63b</td>
<td>12.50c</td>
<td>0.141</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

*Means within a row that have different superscripts differ P < 0.05.

Table 3. Coliform bacterial growth or death rate (CFU h⁻¹) in response to various organic acids at 100 mM (Knarreborg et al., 2002).

<table>
<thead>
<tr>
<th>Culture Media</th>
<th>Control</th>
<th>Fumaric</th>
<th>Lactic</th>
<th>Propionic</th>
<th>Butyric</th>
<th>Formic</th>
<th>Benzoic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stomach content, pH 4.5</td>
<td>-0.25</td>
<td>-2.31</td>
<td>-1.39</td>
<td>-0.19</td>
<td>-1.16</td>
<td>-0.69</td>
<td>&lt;-7.00</td>
</tr>
<tr>
<td>Small intestinal content, pH 5.5</td>
<td>1.16</td>
<td>1.39</td>
<td>0.69</td>
<td>0.07</td>
<td>-0.06</td>
<td>-0.13</td>
<td>-0.69</td>
</tr>
</tbody>
</table>