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Organic acids for performance enhancement in pig diets

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Abstract

Organic acids and their salts appear to be potential alternatives to prophylactic in-feed antibiotics and growth promoters in order to improve the performance of weaned piglets, fattening pigs and reproductive sows, although their growth-promoting effects are generally less than that of antibiotics. Based on an analysis of published data, the growth-promoting effect of formates, fumarates and citrates did not differ in weaned piglets. In fattening pigs, formates were the most effective followed by fumarates, whereas propionates did not improve growth performance. These acids improved the feed : gain ratio of both weaned piglets and fattening pigs. In weaned piglets, the growth-promoting effects of dietary organic acids appear to depend greatly on their influence on feed intake. In sows, organic acids may have anti-agalactia properties. Successful application of organic acids in the diets for pigs requires an understanding of their modes of action. It is generally considered that dietary organic acids or their salts lower gastric pH, resulting in increased activity of proteolytic enzymes and gastric retention time, and thus improved protein digestion. Reduced gastric pH and increased retention time have been difficult to demonstrate, whereas improved apparent ileal digestibilities of protein and amino acids have been observed with growing pigs, but not in weaned piglets. Organic acids may influence mucosal morphology, as well as stimulate pancreatic secretions, and they also serve as substrates in intermediary metabolism. These may further contribute to improved digestion, absorption and retention of many dietary nutrients. Organic acid supplementation reduces dietary buffering capacity, which is expected to slow down the proliferation and/or colonization of undesirable microbes, e.g. *Escherichia coli*, in the gastro-ileal region. However, reduced scouring has been observed in only a few studies. As performance responses to dietary organic acids in pigs often varies, more specific studies are necessary to elucidate an explanation.

Performance enhancers: Organic acids: Growth

Introduction

Intensification of pig farming has led to shortening of the suckling period of piglets from 5–6 to 3–4 weeks of age in order to maximize annual sow productivity. A side effect of this is a higher

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Abbreviations: AID, apparent ileal digestion; ATTD, apparent total tract digestibility; BW, body weight; CP, crude protein; VFA, volatile fatty acid.

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risk of postweaning diarrhoea, which causes retarded growth, increased mortality and extra medication costs (Jahn & Uecker, 1987; Aumaître *et al.* 1995). Digestive disorders and consequent poor performance can also be a problem in the fattening phase, i.e. when pigs from different rearing compartments or farms are transported, mixed in a fattening unit and changed on to a new diet. In order to prevent diarrhoea and to improve performance, prophylactic doses of antimicrobial feed additives, i.e. antibiotics or antibiotic-like growth promoters, are commonly applied in weaner and grower diets. In recent years, however, public concern over development of resistant pathogen strains and antibiotic residues in animal products has led to pressure to search for alternative means of controlling scours with no hazard for consumers. In this context, organic acids which are natural constituents of some feeds, and occur in body metabolism and the gastrointestinal tract, are attractive alternatives, as they may constitute a prophylactic and growth-promoting measure similar to that provided by antimicrobial feed additives.

Weaning at 3–4 weeks of age exposes piglets to both nutritional and environmental stress, which often results in reduced feed intake, little or no weight gain, and in some instances diarrhoea, morbidity and death. This postweaning lag period is a result of a limited digestive and absorptive capacity due to insufficient production of HCl, pancreatic enzymes and sudden changes in feed consistency and intake (Aumaître *et al.* 1995; Cranwell, 1995). At this age the immunological status of a piglet is also low as passive immunity acquired through maternal colostrum is dramatically decreased, and active immunity is only beginning to develop (Gaskin & Kelley, 1995). Lowering dietary pH by weak organic acids, such as citric, formic, fumaric, lactic or propionic acid has been reported to be helpful in overcoming problems of the postweaning lag period (Falkowski & Aherne, 1984; Henry *et al.* 1985).

Although the organic acid supplementation was initially targeted for weaned piglets, there is growing evidence that dietary acidification may also be beneficial for the performance of fattening pigs. Recent results have indicated that in fattening pigs organic acids improved the apparent ileal digestibility of protein and amino acids (Mosenthin *et al.* 1992; Kemme *et al.* 1995; Mroz *et al.* 1997) and absorption of minerals (Jongbloed & Jongbloed, 1996). This may contribute not only to improved performance but also to reduced N and P excretion. In recent years, pig husbandry worldwide has been under increasing pressure to develop feasible solutions to improve the efficiency of N and P utilization and to decrease their excretion. Dietary acidification may be an option to get closer to this target. Organic acids are also known as effective preservatives which protect stored feeds against undesirable bacterial or fungal growth (Frank, 1994), and improved quality of feeds over time may further contribute to improved performance.

The aim of this review is to evaluate the response of weaned piglets, growing pigs and reproductive sows to dietary organic acids as illustrated in terms of performance, i.e. growth rate, feed intake and feed utilization. In addition, reasons for varying responses to and possible modes of action of organic acids will be discussed. A brief summary of the properties of particular organic acids will be given at the beginning of this review.

Properties, absorption and metabolism of organic acids

Organic acids (C1–C7) are widely distributed in nature as normal constituents of plants or animal tissue. They are also formed through microbial fermentation of carbohydrates predominantly in the large intestine of pigs. Some physical and chemical properties of organic acids that are used as acidifiers in pig diets are presented in Table 1. Many of them are also available as sodium, potassium or calcium salts. The advantage of salts over free acids is that

Table 1. Formulas, physical and chemical characteristics of organic acids used as dietary acidifiers for pigs (Foegeding & Busta, 1991)

Acid	Formula	MM (g/mol)	Density (g/ml)	Form	pK_a	Solubility in water
Formic	$HCOOH$	46·03	1·220	liquid	3·75	∞
Acetic	CH_3COOH	60·05	1·049	liquid	4·76	∞
Propionic	CH_3CH_2COOH	74·08	0·993	liquid	4·88	∞
Butyric	$CH_3CH_2CH_2COOH$	88·12	0·958	liquid	4·82	∞
Lactic	$CH_3CH(OH)COOH$	90·08	1·206	liquid	3·83	*v*
Sorbic	$CH_3CH:CHCH:CHCOOH$	112·14	1·204	solid	4·76	*s*
Fumaric	$COOHCH:CHCOOH$	116·07	1·635	solid	3·02 4·38	*s*
Malic	$COOHCH_2CH(OH)COOH$	134·09		liquid	3·4 5·1	∞
Tartaric	$COOHCH(OH)CH(OH)COOH$	150·09	1·760	liquid	2·93 4·23	*v*
Citric	$COOHCH_2C(OH)(COOH)CH_2COOH$	192·14	1·665	solid	3·13 4·76 6·40	*v*

MM, molecular mass expressed in grams.
∞, soluble in all proportions; *v*, very soluble; *s*, sparingly soluble.

they are generally odourless and easier to handle in the feed manufacturing process owing to their solid and less volatile form. They are also less corrosive and may be more soluble in water than the free acids.

Rather than dietary acidifiers, organic acids are better known as effective preservatives. Their primary antimicrobial action (strain-selective growth inhibition or delay) is through pH depression of the diet. However, more importantly the ability of organic acids to change from undissociated to dissociated form, depending on the environmental pH, makes them effective antimicrobial agents. When acid is in the undissociated form it can freely diffuse through the semipermeable membrane of micro-organisms into their cell cytoplasm. Once inside the cell, where the pH is maintained near 7, the acid will dissociate and suppress cell enzymes (decarboxylases and catalases) and nutrient transport systems (Lueck, 1980). The efficacy of an acid in inhibiting microbes is dependent on its pK_a value which is the pH at which 50 % of the acid is dissociated. Organic acids with higher pK_a values are more effective preservatives and their antimicrobial efficacy is generally improved with increasing chain length and degree of unsaturation (Foegeding & Busta, 1991).

Formic acid

Formic acid is a colourless, transparent liquid with a pungent odour. It is commonly used as a preservative in ensiling forage and various by-products which contain less substrate for the desirable production of lactic acid by lactobacilli. Formate is a natural constituent of animal tissue and blood. It is metabolically important in the transfer of 1-C intermediary substances which are generated primarily during amino acid metabolism, and serves as a substrate for biosynthesis of purine bases and thus nucleic acids (Stryer, 1988). Accumulation of formate in the body causes the toxic symptoms of methanol poisoning, i.e. metabolic acidosis, ocular pathological changes and death (Tephly, 1991). Acute toxicity (LD_{50}) after oral application of formic acid is 1–2 g/kg body weight (BW; Lueck, 1980). Sodium and potassium formates are less acutely toxic.

Ingested formic acid is readily absorbed through mucous membranes. In undissociated form it can rapidly diffuse across the cell membrane. The absorption mechanism is similar to that of other short-chain fatty acids (Chang & Rao, 1994). Most of the absorbed formic acid is transported to the liver where it enters the body's 1-C pool and is oxidized to CO_2 and H_2O. The remaining portion can be excreted as its alkaline salts (formates) via the kidneys. The first stage that formate goes through while entering the 1-C pool of the body is to combine with tetrahydrofolic acid to form 10-formyltetrahydrofolate in a reaction catalysed by 10-formyltetrahydrofolate synthetase (*EC* 6.3.4.3). The 10-formyltetrahydrofolate is then oxidized to CO_2, a process mediated by 10-formyltetrahydrofolate dehydrogenase (*EC* 1.5.1.6) (Johlin *et al.* 1987, 1989). The rate of formate oxidation depends on the hepatic folic acid level, particularly that of tetrahydrofolate. Pigs have extremely low hepatic folate levels and very low levels of 10-formyltetrahydrofolate dehydrogenase, a key enzyme in the folate pathway, and thus their ability to metabolize formate is limited (Johlin *et al.* 1987; Makar *et al.* 1990). However, hepatic folate reserves in pigs can be effectively increased by dietary folate supplementation (Letendre *et al.* 1991). It has been shown with mink that the rate of formate oxidation is increased when diets are supplemented with folic acid (Pölönen *et al.* 1997).

Formic acid is an effective acidulant, but it can also inhibit microbial decarboxylases and enzymes such as catalases. Overall, the antimicrobial activity of formic acid is primarily against yeasts and some bacteria, whereas lactic acid bacteria and moulds are relatively resistant to its effects (Lueck, 1980). Formic acid is effective in small concentrations (21·7 mM) against *E. coli.* In addition, formic acid treatment can effectively eliminate salmonella from contaminated feeds (Frank, 1994).

Acetic, propionic and butyric acids

Acetic acid is a colourless liquid with a pungent odour. It is produced through oxidation of alcohol by *Acetobacter* bacteria. Propionic and *n*-butyric acids are both oily liquids and have disagreeable rancid odours. Propionic acid is produced by *Propionibacterium* in the manufacture of cheese (Foegeding & Busta, 1991). It also arises as a metabolite in the degradation of valine (Stryer, 1988). Acetic, propionic and butyric acids are the major end products of bacterial fermentation of dietary fibre in the colon of the pig and they are absorbed by passive diffusion (Kidder & Manners, 1978). Absorption rate depends greatly upon the pK_a and the luminal pH. When the luminal pH is below the pK_a, short-chain fatty acids are absorbed very rapidly. Because the luminal pH in ileum, caecum and colon of the pig is generally greater than 6·5, most short-chain fatty acids remain in their dissociated form and are poorly absorbed. However, Na–H ion exchange by the epithelial cells may decrease the local pH at the absorptive surface, leading to a shift from the ionic to the free acid state, and the absorption proceeds because of a concentration gradient between the lumen and epithelial cells (Chang & Rao, 1994).

Absorbed acetate and butyrate, including those formed in the intermediary metabolism, enter the citric-acid cycle after being converted to acetyl-CoA. The major metabolic route of propionate is to succinyl-CoA with methylmalonyl-CoA as an intermediate (Stryer, 1988). A small portion of propionate is converted to lactate by the epithelial cells which also appear to oxidize acetate completely (McDonald *et al.* 1995).

As a preservative, acetic acid inhibits the growth of many species of bacteria, and to a lesser extent of yeasts and moulds. The action of propionic acid is primarily against moulds. It has only poor activity against bacteria and none against yeasts, since the latter can metabolize it (Foegeding & Busta, 1991). The minimum concentration of acetic or propionic acid that prevents *E. coli* is 0·5 %, which is five times higher than that of formic acid (Frank, 1994).

Lactic acid

Lactic acid is produced by many bacterial species, primarily those of the genera *Lactobacillus*, *Bifidobacterium*, *Streptococcus*, *Pediococcus* and *Leuconostoc*. It is a natural constituent of some feedstuffs and is among the oldest of the preservatives. The antimicrobial action of lactic acid is directed primarily against bacteria, whereas many moulds and yeasts can metabolize it (Foegeding & Busta, 1991).

In the stomach and small intestine, lactic acid is produced as an end product of sugar fermentation. Lactate is also produced by muscle cells from glycogen when the oxygen supply is inadequate to support pyruvate oxidation and ATP production via aerobic metabolism. The lactate entering the blood stream either from muscles or from the gastrointestinal lumen is carried to the liver where it is reoxidized to pyruvate. Pyruvate can then be oxidized via the citric-acid cycle (Stryer, 1988).

Citric and fumaric acids

Citric and fumaric acids are both crystalline and odourless. Citric acid has a pleasant sour taste and fumaric acid has a tart flavour. Citric acid is generally a less effective antimicrobial agent than other organic acids, partly because many micro-organisms can metabolize it and also because of a low pK_a (Foegeding & Busta, 1991).

Dietary fumarate and citrate are absorbed by a common Na^+-gradient mechanism which is specific for tri- and dicarboxylates (Wolffram *et al.* 1990, 1992). In the pig, fumaric acid arises as a metabolite from the degradation of phenylalanine and tyrosine and also occurs as an intermediate in the urea cycle and during purine synthesis. Fumarate and citrate formed in the intermediary metabolism, as well as those of dietary origin, are directed to the citric-acid cycle where they serve as important intermediary metabolites (Stryer, 1988).

Other acids

A number of other organic acids, e.g. malic, tartaric and sorbic acids, and acid blends have also been studied as dietary acidifiers for pigs. Malic is naturally found in apples and many other fruits and is active against certain bacteria and yeasts. Tartaric acid, which is the primary acid of grapes, has a strong acid taste. Sorbic acid is present in certain berries and has a distinctive odour and sour taste; it is considered non-toxic and is metabolized via β- and ω-oxidation, as are the long-chain fatty acids. The LD_{50} for sorbic acid is in the range 7–11 g/kg BW. Sorbic acid inhibits yeasts, moulds and some bacteria. Its antimicrobial action is due to the inhibition of enzymes and nutrient transport (Foegeding & Busta, 1991).

Organic acids and pig performance

To evaluate the effects of dietary organic acids on performance (average daily gain, feed intake and feed : gain ratio) of weaned piglets and fattening pigs, data were collected from the literature and subjected to a meta-analysis (Hedges & Olkin, 1985). Studies in which the following criteria were reported were chosen for the analysis: initial and final weight of pigs, average daily gain, feed intake, feed : gain ratio and their standard deviations, number of observations per treatment, diet composition (simple or complex, with or without dairy products) and feed allowance (*ad lib.* or restricted). Dietary organic acid levels (g/kg) were converted to milliequivalents (mequiv./kg) to make the levels of different acids more comparable.

Experimental diets which contained other growth promoters, e.g. antimicrobial feed additives, Cu or probiotics, in addition to organic acids, were excluded from the data. Acid blends were also excluded from the data, since their composition was seldom reported and it was impossible to calculate accurate acid levels as milliequivalents.

The unbiased effect size (response) d was calculated on the basis of the standardized mean difference adjusted for sample size (Hedges & Olkin, 1985) as follows:

$$d \cong (1 - 3/(4N - 9))(Y^{\mathrm{E}} - Y^{\mathrm{C}})/s,$$

where N is the total sample size, Y^{E} and Y^{C} are the respective experimental and control group means and s is their pooled standard deviation. Positive values indicate an increase and negative values a decrease in performance response. The effect size data were analysed by the procedure for mixed models by SAS (Littell *et al.* 1996). The final models used to describe the response in growth and feed : gain ratio were chosen on the basis of log likelihood ratios (Table 2). For weaned piglets the models for both growth and feed : gain ratio response included the effects of acid, dietary acid level, feed intake (unbiased effect size) and acid × feed intake interaction (model 3), and for fattening pigs the effects of acid and acid level (model 2).

Table 2. Selection of models used for the meta-analysis of published data

Model	Acid	Level	Acid × level	Level^2	Acid × level^2	Feed intake	Acid × feed intake	−2 log likelihood	df	*P*
Weaned piglets										
Average daily gain										
1	x	x	x	x	x	x	x	−6·0322	26	
2	x	x	x			x	x	0·5116	29	0·088
3	x	x				x	x	3·2244	31	0·258
Feed to gain										
1	x	x	x	x	x	x	x	119·1687	20	
2	x	x	x			x	x	115·4194	22	0·153
3	x	x				x	x	115·9182	24	0·779
Fattening pigs										
Average daily gain										
1	x	x	x					22·0198	14	
2	x	x						24·3769	16	0·502
Feed to gain										
1	x	x	x					18·1295	14	
2	x	x						19·6458	16	0·471

df, degrees of freedom.
P, probability that the model differs from the preceding model.

Weaned piglets

Fumaric and citric-acids are the most commonly studied organic acids in weaner diets. Recently, an increasing interest has been directed towards formic acid and its calcium, sodium or potassium salts. In general, dietary organic acids seem to improve the growth performance and feed : gain ratio of weaned piglets (Fig. 1; Table 3) but the responses vary greatly, ranging from −58 g/d (BW losses) up to +106 g/d (BW gain). Potential reasons for the varying results may relate to differences in the type and dose of acid used, composition of basal diet, age of animals, and existing levels of performance (Ravindran & Kornegay, 1993).

Type and level of acid. On average, formic acid or formates, fumaric acid and citric-acid improved the average daily gain of weaned piglets and reduced the feed : gain ratio relative to the non-acidified control diet (Table 3). In the range of acid levels studied (<450 mequiv./kg), growth response increased ($b = 0{\cdot}0087$ (SD 0·0003), $P < 0{\cdot}01$) and feed : gain ratio decreased ($b = -0{\cdot}0040$ (SD 0·0010), $P < 0{\cdot}001$) slightly with increasing dietary acid level. From these data it was not possible to find an optimal level of dietary organic acid. Differences between the acids studied (formic acid or formates, fumaric acid and citric-acid) were not significant. Other acids, e.g. acetic (Roth & Kirchgessner, 1988), lactic (Schulz & Fischer, 1983; Roth *et al.* 1993) and sorbic acid (Kirchgessner *et al.* 1995), have also shown growth-promoting effects, but the number of experiments was too small to be included in the meta-analysis. The growth-promoting effects of dietary organic acids appear to be smaller than those of antibiotics or antibiotic-like growth promoters. Organic acids can also enhance the effects of antibiotics by improving their absorption (Petersen & Oslage, 1982*b*; Edmonds *et al.* 1985; Radecki *et al.* 1988; Eidelsburger *et al.* 1992*b*).

The growth and feed : gain responses of weaned piglets to dietary organic acids were best explained when the changes in feed intake were included in the model, since performance responses were closely related to changes in feed intake (Fig. 2). However, with the information available from the literature it was not possible to find a satisfactory model to explain the effects of dietary organic acids on feed intake. Previously improved growth of piglets fed on acidified diets has been ascribed to a better diet palatability (Cole *et al.* 1968; Bolduan *et al.* 1988*a*,*b*). The literature data indicate that different organic acids may have different effects on feed intake: in general, dietary formic acid or formates had a positive effect, fumaric acid had no effect and citric-acid had a negative effect. These effects may also be related to the age of the piglets, younger piglets being more sensitive to the changes in diet palatability. Although the growth-promoting effects of dietary organic acids appear to depend greatly on how they improve feed intake, so far hardly any attention has been paid to the influence of organic acids on the palatability of prestarter or starter diets. In the study of Henry *et al.* (1985), when free access was allowed to both acidified and non-acidified (citric and fumaric acids) diets, pigs consumed significantly more of the non-acidified diet.

Certain acids, e.g. tartaric and formic acids, have a strong odour and flavour, and an increasing dietary acid level is generally associated with a dramatic decrease in feed intake, as reflected by lower daily gains (Eckel *et al.* 1992*a*; Kirchgessner *et al.* 1993). Addition of excessive amounts of formates to the diet may also disturb the acid–base status of pigs leading to metabolic acidosis, which results in decreased feed intake and slower growth (Giesting *et al.* 1991; Eckel *et al.* 1992*a*; Eidelsburger *et al.* 1992*e*; Grassmann *et al.* 1992). Organic acids metabolized via the citric-acid cycle, e.g. fumaric and citric-acids, do not seem to cause acidosis, irrespective of their dietary inclusion (Eidelsburger *et al.* 1992*c*).

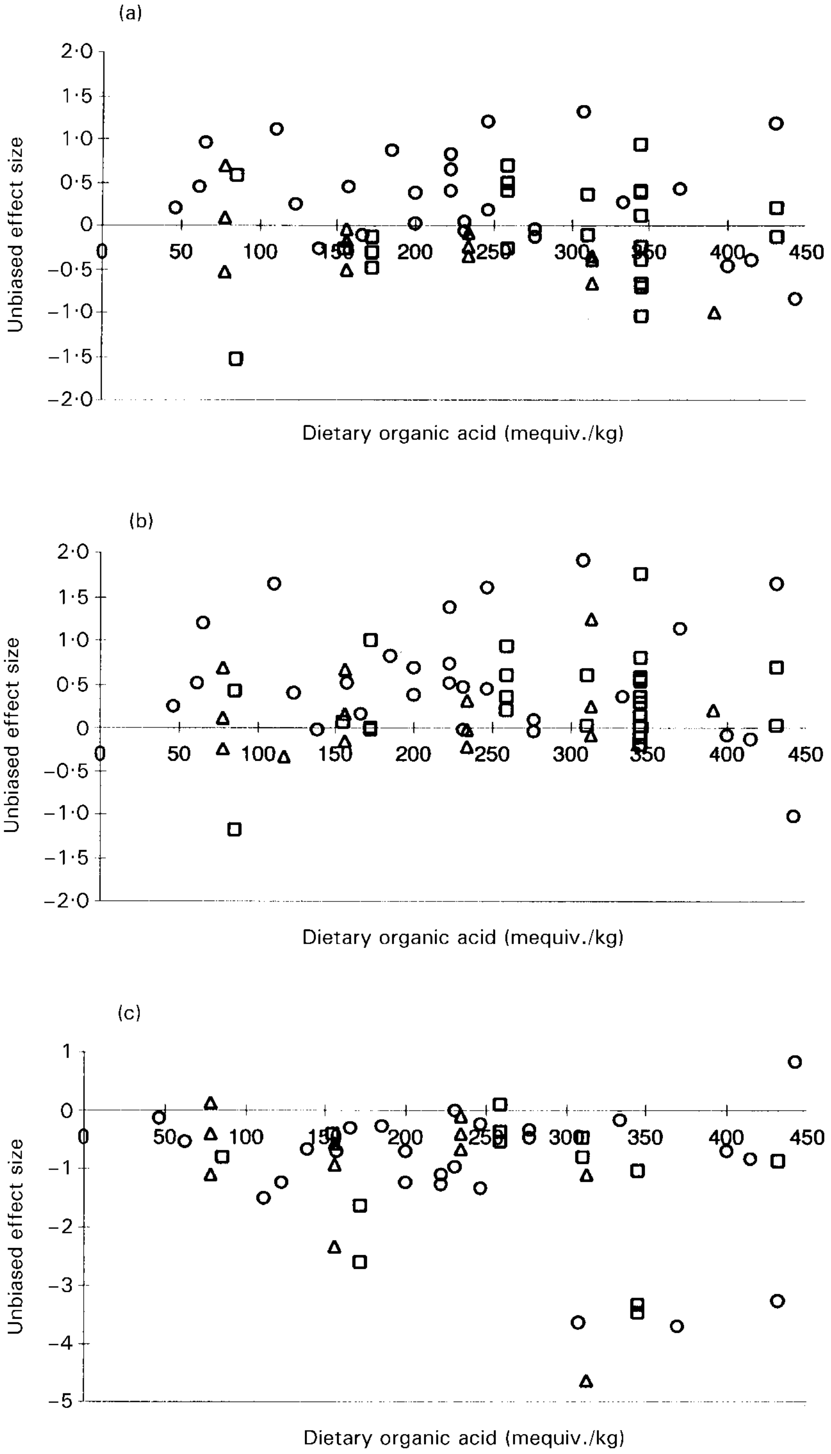

Fig. 1. The effect of dietary formic acid or formates (○), fumaric acid (□) and citric acid (△) on (a) feed intake, (b) average daily BW gain and (c) feed : gain ratio of weaned piglets relative to non-acidified control diets.

Table 3. Response of weaned piglets and fattening pigs to dietary organic acids or their salts according to the meta-analyses of published data

				Unbiased effect size					
Organic acid	Number of experiments	*n* total	Range of acid level (mequiv/kg)	Average daily bodyweight gain (kg)	SEM	*P*	Feed : gain	SEM	*P*
Weaned piglets*									
Formic acid and formates	11	27	46–444	0·269	0·0766	0·001	−0·721	0·2542	0·007
Fumaric acid	15	25	86–431	0·409	0·0702	<0·001	−0·899	0·2802	0·004
Citric acid	9	14	78–391	0·255	0·1106	0·028	−0·829	0·3753	0·037
Fattening pigs†									
Formic acid and formates	7	13	77–231	0·750	0·1663^{a}	<0·001	−0·655	0·1385	<0·001
Propionic acid and propionates	5	10	92–405	0·134	0·1940^{b}	0·499	−0·558	0·1599	0·003
Fumaric acid	4	10	103–431	0·655	0·2122^{a,b}	0·007	−0·651	0·1933	0·004

P, probability that acidified diets differ from non-acidified control diet.

^{a,b}Means within a column and animal type not sharing a common superscript letter were significantly different, $P<0·05$.

* References: Kirchgessner & Roth-Maier, 1975; Kirchgessner & Roth, 1976, 1978*a*, 1982, 1987*a*, *b*, 1990; Roth & Kirchgessner, 1982; Falkowski & Aherne, 1984; Giesting & Easter, 1985, 1991; Broz & Schulze, 1987; Bolduan *et al.* 1988*a*,*b*; Giesting *et al.* 1991; Risley *et al.* 1991; Eckel *et al.* 1992*a*; Eidelsburger *et al.* 1992*b*,*d*; Kirchgessner *et al.* 1993, 1997; Krause *et al.* 1994; Paulicks *et al.* 1996; Roth *et al.* 1996.

† References: Thacker & Bowland, 1980; Thacker *et al.* 1981, 1992; Kirchgessner & Roth, 1982, 1989; Petersen & Oslage, 1982*a*; Roth & Kirchgessner, 1982; Schulz & Oslage 1982; Giesting & Easter, 1985; Baustad, 1993; Kirchgessner *et al.* 1997; Øverland & Lysø, 1997.

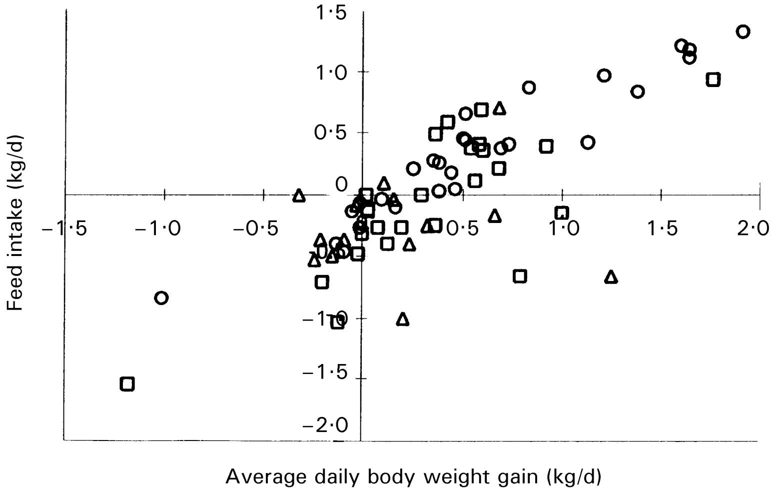

Fig. 2. The relationship between feed intake and growth response (unbiased effect size) of weaned piglets to dietary formic acid or formate (○), fumaric acid (□) and citric acids (△) supplementation.

Type of diet. The literature data did not allow the effect of diet type (simple or complex, with or without dairy products) on the growth-promoting effects of dietary organic acids to be differentiated, as diet type was often confounded with the age of piglet, i.e. prestarter diets generally contained milk products whereas weaner diets were without them. However, a few studies indicate that the response of weaned piglets to organic acids may depend on ingredient and chemical composition of the diet. The greatest acidification benefits have been observed when diets were formulated from cereals and plant proteins, while the growth-promoting effect was small in diets containing milk products (Burnell *et al.* 1988; Giesting *et al.* 1991; Weeden *et al.* 1991; Roth *et al.* 1993). The latter presumably holds true when lactose in milk products is converted to lactic acid by lactobacilli in the stomach, creating the desired reduction in pH and thus reducing the need for diet acidification (Easter, 1988).

The observed differences in performance responses to dietary organic acids may also be due to differences in dietary buffering capacity (Bolduan *et al.* 1988*a*,*b*). The buffering capacity varies substantially between different feedstuffs. The acid-buffering capacity is lowest in cereals and cereal by-products, intermediate or high in protein feedstuffs and very high in mineral sources, except in dicalcium and monosodium phosphates (Jasaitis *et al.* 1987). Also the shape of titration curves varies greatly between feedstuffs (Wohlt *et al.* 1987). Addition of organic acids reduces dietary pH curvilinearly depending on the acid pK_a value and buffering capacity of the diet. The pH-lowering effect of different organic acids is reduced in the following order: tartaric acid > citric-acid > malic acid > fumaric acid > lactic and formic acids > acetic acid > propionic acid. Organic salts have only a small influence on dietary pH. Addition of protein and mineral sources to the diet weakens the pH-lowering effect of the acid (Roth & Kirchgessner, 1989*a*). It seems reasonable to assume that the buffering capacity of a pig feed can be considerably influenced by selection of feed ingredients, and it may in part reflect on differences in the effectiveness of acidifiers. In general, organic acids lower dietary buffering capacity, whereas certain organic salts can increase it. However, Roth & Kirchgessner (1989) found no direct relationship between piglet performance and reduction in dietary buffering capacity.

Weaning age and existing level of performance. Organic acid supplementation appears to be most effective during the first 2–4 weeks after weaning, and the effect declines as the pig matures (Giesting *et al.* 1991). Ravindran & Kornegay (1993) suggested that a better performance could be expected in conditions which are suboptimal for growth of piglets. However, Risley *et al.* (1993) failed to observe any measurable effect of supplementation of 15 g citric or fumaric acid/kg diet on postweaning growth performance or scouring when piglets were challenged with enterotoxigenic *E. coli.* Based on published data, the existing level of performance (average daily gain of control group) did not seem to influence performance responses to dietary organic acids.

Fattening pigs and sows

A summary of the literature data concerning changes in average daily gain and feed : gain ratio of fattening pigs relative to different levels of dietary organic acids is presented in Fig. 3 and Table 3. The dietary acid level range was limited to <450 mequiv./kg. With higher levels of propionates a reduction in average daily BW gain has been observed as a result of decreased feed intake (Thacker & Bowland, 1980, 1981; Thacker *et al.* 1981; 1992), possibly due to the strong odour and flavour of propionates. In the range of acid levels studied, the responses ranged from −50 g/d (BW losses) to +58 g/d (BW gain). Formic acid or formates were the most effective, followed by fumaric acid. The effect of propionates did not differ from zero. All these acids improved the feed : gain ratio of fattening pigs, but differences between the acids were not significant. Other organic acids or their salts, e.g. lactic acid, sodium butyrate, have also been shown to be effective growth promoters in fattening pigs (Gálfi & Bokori, 1990; Jongbloed & Jongbloed, 1996).

Feeding regimen (*ad lib.* or restricted) did not seem to influence the growth-promoting effects of organic acids, although the highest responses have been observed when the pigs have had *ad lib.* access to feed. In general, the performance response of growing pigs to organic acids and their salts seems to be more consistent than that of weaned piglets. The response was somewhat higher in the grower than finisher phase (Kirchgessner & Roth, 1978*a*, 1989; Kirchgessner *et al.* 1997). There were too few data to draw conclusions about the effect of diet type on the efficacy of dietary organic acids, but it seems that the largest benefits have been observed with complex by-product-based diets.

The effects of formic acid (10 g/kg diet) for pregnant and lactating sows on performance and some agalactia-related criteria were presented by Mroz *et al.* (1998). The authors concluded that body mass changes over the whole cycle (pregnancy+lactation) were not influenced by formic acid, whereas the total feed intake during pregnancy was up to 7·7 kg lower ($P<0{\cdot}05$) in sows fed on formic acid. Reproductive performance of sows receiving formic acid as illustrated in terms of litter size and piglet birth weight and weight at weaning was slightly better in the presence of formic acid in pregnancy and lactation diets, but the differences were not statistically significant. Data on health status and agalactia-related indices showed preventive, anti-agalactia properties of formic acid. Folic acid (or folate) plays a major coenzymic role in 1-C metabolism (Kokue *et al.* 1994). Makar *et al.* (1990) have shown that the pig compared with all other species has extremely low levels of folates and very low levels of a key enzyme in the folate pathway, 10-formyltetrahydrofolate dehydrogenase. Also, the pig's ability to

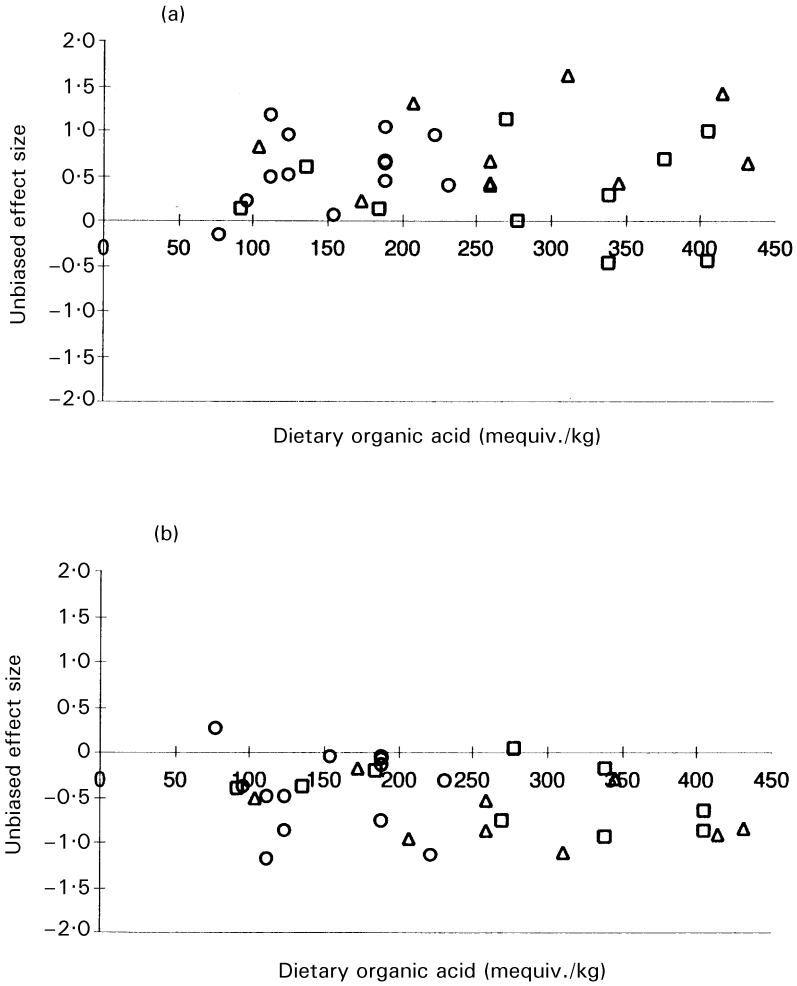

Fig. 3. The effect of dietary formic acid or formates (○), propionic acid or proprionates (□) and fumaric acid (△) on (a) average daily body weight gain and (b) feed : gain ratio of fattening pigs relative to non-acidified control diet.

dispose of formate was extremely limited and slower than that observed in rats or monkeys. This implies that the rate of formate oxidation is dependent on adequate levels of hepatic folic acid, particularly hepatic tetrahydrofolate. Some studies suggest that the dietary source of folic acid may not be optimal for weanling pigs (Letendre *et al.* 1991) and sows (Lindemann, 1993). So far, no dose–response interactive effects of formic acid and folic acid levels as two independent variables in diets for pigs have been published. Further studies of formic acid in combination with bioactive folic acid would be desirable.

Physiological factors affected by the action of organic acids

Successful application of organic acids in diets for pigs requires an understanding of their modes of action. Although several hypotheses have been proposed, their exact mode of action still remains unclear. It is generally considered that dietary organic acids or their salts lower gastric pH and this results in increased activity of proteolytic enzymes and gastric retention time. Due to the lower rate of gastric emptying, large protein molecules may be better hydrolysed, which will have a beneficial effect on protein digestion (Easter, 1988; Kirchgessner & Roth, 1988; Ravindran & Kornegay, 1993; Gabert & Sauer, 1994). A reduced buffering capacity of diets containing organic acids is also expected to slow down the proliferation and/or colonization of undesirable microbes, e.g. *E. coli*, in the gastro-ileal region. As particular organic acids have strong antimicrobial activities, it seems appropriate that their positive influence on digestion may be related to indirect effects on gastrointestinal microbes. Besides, organic acids can influence mucosal morphology, as well as stimulate pancreatic secretions and serve as substrates in the intermediary metabolism. This multifunctional role of organic acids may lead to the improved digestion, absorption and retention of numerous dietary nutrients.

pH of digesta

Low gastric pH is essential for efficient digestion of proteins. Pepsinogens are rapidly activated at pH 2, but very slowly at pH 4. Pepsin has two pH optima: 2 and 3·5. Its activity declines rapidly when pH rises above 3·6, and remains inactive at pH 6 (Kidder & Manners, 1978). The endproducts of pepsin digestion and the low pH of digesta entering the duodenum are involved in the stimulation of the pancreatic secretion of enzymes and bicarbonate, and they also play a minor role in regulation of gastric emptying (Maner *et al.* 1962; Argenzio, 1984). Acid conditions are also needed to prevent passage of potentially harmful microbes to the small intestine. A rise in gastric pH with inefficient digestion may provide an optimal environment for the colonization of enterotoxigenic haemolytic bacteria on the surface of villi, resulting in the initiation of scours and/or oedema disease in young pigs, particularly after weaning (Smith & Jones, 1963).

The hypothesis that lowering dietary pH with organic acids reduces gastrointestinal pH has been tested in several studies (Table 4). Perhaps owing to methodological imperfections, only a few studies could document that dietary acidification significantly decreased gastric pH (Bolduan *et al.* 1988*a*,*b*; Eidelsburger *et al.* 1992*b*; Radcliffe *et al.* 1998) whereas most studies have failed to show any significant effect despite quite a large numerical decrease in pH (Scipioni *et al.* 1978; Burnell *et al.* 1988; Risley *et al.* 1992; Gabert & Sauer, 1995). High variations in gastric pH measurements indicate that it is difficult to obtain a representative sample, as the proportions of feed and endogenous excretions can vary from sample to sample. Digesta samples for pH measurements are generally taken from pigs slaughtered after a certain time postfeeding. As the diurnal variation in gastrointestinal pH is large, the sampling time should be standardized relative to feeding time, and eventually from specific sections of the stomach. Without cannulation techniques and permanently fixed pH electrodes for simultaneous measurements in different sections of the stomach and intestine it may be difficult to assess objectively the full effects of dietary organic acids on the gastrointestinal pH.

Rate of gastric emptying

Mainly the volume of digesta in the stomach and, perhaps to a lesser degree, the pH in the pyloric region stimulate its emptying rate (Kidder & Manners, 1978; Mayer, 1994). As already mentioned, at increased acidity of digesta the rate of gastric emptying is reduced, which allows more time for protein hydrolysis in the stomach (Mayer, 1994). Table 4 summarizes the influence of diet acidification on DM content in the stomach, as evaluated *post mortem.* At a

Table 4. Influence of dietary organic acids or their salts on pH values of digesta in different sections of gastrointestinal tract and gastric dry matter content

Acidifier	Reference	Level (g/kg)	Gastrointestinal pH				Gastric dry matter content
			Gastric	Ileal	Caecal	Colonic	
Citric acid	Scipioni *et al.* 1978	10	ns	ns			
	Risley *et al.* 1991	15	ns	ns	ns	ns	
	Risley *et al.* 1992	15	ns	ns	ns	ns	
	Risley *et al.* 1993	15	ns	ns	ns	ns	
	Fasshauer & Kienzle, 1995	10		−			
	Radcliffe *et al.* 1998	15	−				
		30	−				
Formic acid	Bolduan *et al.* 1988*a*	3·5	−	ns			ns
		12	−	ns			ns
	Eidelsburger *et al.* 1992*a*	12·5	−	ns	ns	ns	ns
	Roth *et al.* 1992*a*	6	ns	ns	ns	ns	ns
		12	ns	ns	ns	ns	ns
		18	ns	+	+	+	ns
		24	ns	+	ns	+	ns
	Gabert & Sauer, 1995	10		ns			
Fumaric acid	Bolduan *et al.* 1988*b*	5	ns				ns
		15	−				ns
	Risley *et al.* 1991	15	ns	ns	ns	ns	
	Risley *et al.* 1992	15	ns	ns	ns	ns	
	Risley *et al.* 1992	18	−	ns	ns	ns	ns
	Risley *et al.* 1993	15	ns	ns	ns	ns	
	Gabert & Sauer, 1995	15		ns			
		30		ns			
Propionic acid	Bolduan *et al.* 1988*a*	3	ns	ns			ns
		10	ns	ns			ns
Calcium formate	Eidelsburger *et al.* 1992*a*	10	ns	ns	ns	ns	ns
		18	ns	ns	ns	ns	ns
Sodium formate	Roth *et al.* 1992*b*	18	ns	ns	ns	ns	−
Sodium fumarate	Gabert & Sauer, 1995	15		ns			ns

+, significant increase in pH or dry matter content ($P<0{\cdot}05$); −, significant decrease in pH or dry matter content ($P<0{\cdot}05$); ns, no significant influence on pH or dry matter content.

similar volume (=meal size) of digesta, DM contents in the stomach reflect proportionally the rate of gastric emptying. Since no statistically significant differences were found in gastric DM contents among the cited studies (except for sodium formate by Roth *et al.* 1992*b*), these results do not support the hypothesis that organic acids influence the rate of gastric emptying. Subsequently, if there is no retarded gastric emptying due to organic acids, a meaningful improvement of digestion and absorption of nutrients in the small intestine is less probable. However, bearing in mind the shortcomings of the *post mortem* technique, more specific, fundamental studies on gastric emptying rate using gastrically and/or duodenally cannulated pigs and markers would be desirable.

Digestibility and retention of nutrients

Total tract digestibility and retention of nutrients and energy. Several researchers have reported improvements in the apparent total tract digestibility (ATTD) and retention of nutrients with dietary acidification of diets for weaned piglets or fattening pigs (Tables 5

Table 5. Influence of dietary organic acids or their salts on the apparent total tract digestibility of crude protein and energy and nitrogen balance in weaned piglets

		Level	Crude protein		Energy		Nitrogen balance	
Acid	(g/kg)	Diet	D (%)	ΔD	D (%)	D	R (%)	ΔR
Citric acid								
Scipioni *et al.* 1978	10	starter	84·9	+2·9	86·5	+1·2		
Falkowski & Aherne, 1984	10	starter	78·4	+0·2				
	20	starter		+1·0				
Broz & Schulze, 1987	5	starter	80·7	+0·8	81·0	+1·0*		
	10	starter		+1·4		+1·9*		
	15	starter		−0·8		+0·6		
Formic acid								
Eckel *et al.* 1992*a*	6	prestarter	86·2	+2·2*	88·4	+0·9		
	12	prestarter		+2·9*		+1·4		
	18	prestarter		+3·8*		+1·9*		
	24	prestarter		+3·8*		+2·2*		
	6	starter	87·0	+1·1	89·3	+0·7		
	12	starter		+1·4		−0.6		
	18	starter		+1·2		+0·4		
	24	starter		+2·6*		+0·5		
Eidelsburger *et al.* 1992*d*	12.5	prestarter	87·8	+2·0*	89·2	+0·5		
	12.5	starter	86·3	+1·0	87·7	+0·7		
Gabert & Sauer, 1995	15	starter	89·2	−0·2	86·6	−0·2		
	30	starter		−0·8		−0·9		
Sodium formate								
Gabert & Sauer, 1995	15	starter	89·2	−1·4	86·6	−0·7		
Calcium formate								
Eidelsburger *et al.* 1992*d*	18	prestarter	87·8	+1·7*	89·2	+0·7		
	18	starter	86·3	+1·3	87·7	+1·0		
Fumaric acid								
Scipioni *et al.* 1978	7	starter	84·9	−2.4	86·5	−2.2		
Kirchgessner & Roth, 1978*b*	18	prestarter	84·0	+0·8	80·2	+1·6*		
	18	starter	84·9	+1·0	82·6	+0·5		
Kirchgessner & Roth, 1980	10	starter	85·2	+2·1	85·9	+1·3*	61·5	+3·1*
	20	starter		+2·5*		+1·8*		+4·1*
Falkowski & Aherne, 1984	10	starter	78·4	+0·5				
	20	starter		+1·4				
Eidelsburger *et al.* 1992*b*	18	prestarter	87·1	+0·4	88·4	+0·6		
	18	starter	86·4	+1·0	87·7	−0·2		
Propionic acid								
Kirchgessner & Roth, 1982	10	prestarter	84·5	+1·5	81·9	+1·4	60·1	+1·0
	20	prestarter		+1·6		+2·2*		+1·8
	10	starter	83·0	+0·2	81·5	−0·1	50·7	+0·3
	20	starter		+0·5		+0·7		+1·5
Calcium propionate								
Roth & Kirchgessner, 1982	10	prestarter	84·5	+1·5	81·9	+1·4		
	20	prestarter		+1·6		+2·2*		
	10	starter	83·0	+0·2	81·5	−0·1		
	20	starter		+0·5		+0·7		

D, digestibility of non-acidified control diet; ΔD, %-unit change in the digestibility relative to the non-acidified control diet; R, nitrogen retention of non-acidified control diet as percentage of intake; ΔR, %-unit change in the nitrogen retention relative to the non-acidified control diet.

* Significantly different from the control diet ($P<0·05$).

and 6). In particular, organic acids exerted a small, positive influence on the ATTD and retention of crude protein (CP) and energy, whereas the influences on other nutrients were found to be less consistent.

The effect of organic acids on ATTD of nutrients and energy seems to depend on the type and level of acid applied. In several experiments, citric-acid exerted no significant influence on ATTD of CP or N retention (Falkowski & Aherne, 1984; Broz & Schulze, 1987; Pallauf *et al.* 1988), although improved digestibilities of organic matter and gross energy have been observed (Broz & Schulze, 1987; Pallauf *et al.* 1988). Citric acid is metabolized through the citric-acid cycle, and may act as an energy source. A positive effect of fumaric acid on ATTD of organic matter, crude fat (diethyl ether extract) and CP, and on N retention have been reported by Kirchgessner & Roth (1978*b*; 1980). However, several researchers have failed to observe any effect of these organic acids on the digestibility of CP and energy or N retention (Falkowski & Aherne, 1984; Radecki *et al.* 1988; Giesting & Easter, 1991; Eidelsburger *et al.* 1992*b*).

Formic acid appears primarily to affect ATTD of CP, whereas the influence on ATTD of organic matter and energy seems to be smaller. Eckel *et al.* (1992*a*) reported that ATTD of CP increased by 2·6 % to 4·4 % ($P<0{\cdot}05$) when complex starter diets designed for piglets from 6 to 14 kg BW were supplemented with 6–24 g formic acid/kg diet. However, the authors found no effect in the subsequent period between 14 and 23 kg BW. The improvement in digestibility of gross energy was significant only at the highest inclusion levels of formic acid (18–24 g/kg diet) in the starter diet. Similarly, Eidelsburger *et al.* (1992*a*,*d*) found that formic acid (12·5 g/kg diet), calcium formate (18 g/kg) and sodium formate (18 g/kg) improved ATTD of CP when added to a complex starter diet for piglets between 6 and 14 kg BW, but not in the subsequent period. It seems that the influence of formic acid or its salts on the digestibility of

Table 6. Influence of dietary organic acids or their salts on the apparent total tract digestibility of crude protein and energy and nitrogen balance in growing pigs

Acid	Level (g/kg)	Diet	Crude protein		Energy		Nitrogen balance	
			D (%)	ΔD	D (%)	ΔD	R (%)	ΔR
Butyric acid								
Mroz *et al.* 1997	26·7	grower	80·6	+1·4	82·2	+1·8	48·3	+4·0**
Formic acid								
Mroz *et al.* 1997	13·8	grower	80·6	+1·4	82·2	+0·7	48·3	+4·9*
Fumaric acid								
Mroz *et al.* 1997	17·6	grower	80·6	−1·0	82·2	+1·4	48·3	+2·9*
Propionic acid								
Kirchgessner & Roth, 1992	10	grower	79·7	+0·3	77·3	+0·3	43·2	−1·1
	20	grower		+1·7		+0·8		+3·8
	10	finisher	78·5	+1·3	77·1	−0·6	38·0	−0·4
	20	finisher		+0·1		−1·7		+0·2
Mosenthin *et al.* 1992	20	grower	80·2	+2·3	77·9	+1·4		
Calcium propionate								
Roth & Kirchgessner, 1982	10	grower	79·7	+0·3	77·3	+0·3		
	20	grower		+1·7		+0·8		
	10	finisher	78·5	+1·3	77·1	−0·6		
	20	finisher		+0·1		−1·7		

D, digestibility of non-acidified control diet; ΔD, %-unit change in the digestibility relative to the non-acidified control diet; R, nitrogen retention of non-acidified control diet as percentage of intake; ΔR, %-unit change in the nitrogen retention relative to the non-acidified control diet.

* Significantly different from the control diet ($P<0{\cdot}05$).

CP is most effective in young piglets with immature digestive systems, and the effect diminishes when the pig matures. However, it should be noted that formic acid has been shown to improve ATTD of nutrients in growing pigs (Jongbloed & Jongbloed, 1996). Using the comparative slaughter technique, Kirchgessner *et al.* (1992) studied the effect of formic acid supplementation (6–24 g/kg diet) on protein, fat, ash and energy retention in weaned piglets. They found that all formic acid-supplemented diets resulted in increased carcass protein content. Compared with the control group, the retention of protein was higher ($P<0{\cdot}05$) in pigs fed on diets with 6–18 g formic acid/kg diet, and averaged 61 g/d. Also, at low levels of supplementary formic acid (6–12 g/kg diet), energy retention was enhanced.

Kirchgessner & Roth (1982) reported that supplementation with propionic acid had no effect on ATTD of DM, CP or gross energy. Similar results have been reported by Bolduan *et al.* (1988*a*). Recently, Jongbloed & Jongbloed (1996) found that propionic acid supplementation increased ATTD of DM and ash, but not that of organic matter. Similar observations were made with lactic acid, which is in agreement with earlier results of Jongbloed *et al.* (1995).

Ileal digestibility of protein and amino acids. Data on the effects of organic acids on the apparent ileal digestibility (AID) of CP and amino acids is scarce. Giesting & Easter (1991) were first to report a non-significant increase in the AID of crude protein when fumaric acid 20 g furmaric acid/kg diet was added to a maize–soyabean meal diet. However, no response

Table 7. Influence of dietary organic acids or their salts on the apparent ileal digestibility of crude protein and amino acids in piglets

Reference . . .	Gabert *et al.* 1995				Gabert & Sauer, 1995			
Diet/acidifier . . .	SFM(n) For(10)		SFM(h) For(10)		WSM Fum(10)		Fum(30)	Na-fum(15)
	D (%)	ΔD	D (%)	ΔD	D (%)	ΔD	ΔD	ΔD
Crude protein	79·5	−1·7	79·3	−4·1	80·3	−0·4	−4·1*	−1·1
Essential amino acid								
Arginine	88·8	+1·0	89·4	−2·1	87·2	−1·4	−4·5*	−1·6
Histidine	85·5	−0·9	85·5	−1·8	85·6	+0·5	−1·3	−0·9
Isoleucine	85·3	+0·7	86·6	−3·6	85·1	−0·5	−1·4	−1·5
Leucine	85·7	0·0	86·0	−3·1	85·3	−0·9	−2·1	−1·7
Lysine	89·0	+0·4	90·9	−3·2	82·6	−1·0	−1·8	−1·9
Methionine	—	—	—	—	—	—	—	—
Phenylalanine	82·4	+0·4	83·1	−3·4	85·0	−1·2	−3·0	−3·0
Threonine	79·7	−0·6	80·3	−5·6	75·5	0·0	−1·5	−1·8
Tryptophan	—	—	—	—	—	—	—	—
Valine	84·3	+0·4	85·7	−3·8	82·4	−0·2	−1·6	−2·1
Nonessential amino acid								
Alanine	85·1	+1·0	86·0	−2·3	76·2	+0·2	−2·7	−1·8
Aspartate	79·8	−2·2	80·1	−4·3	79·8	+0·6	−0·8	−0·1
Cystine	—	—	—	—	—	—	—	—
Glutamate	85·6	+0·6	87·6	−4·7	90·8	0·0	−1·7	−0·5
Glycine	78·0	−1·0	76·6	−2·7	67·7	−1·2	−9·7*	−1·2
Proline	—	—	—	—	—	—	—	—
Serine	79·7	−1·5	79·1	−4·0	80·4	+0·1	−1·8	−1·2
Tyrosine	84·4	+0·1	84·5	−2·8	83·0	+0·7	−3·5*	−1·1

Diet: SFM, semipurified fishmeal diet with normal (n) or high (h) buffering capacity; WSM, wheat–soyabean meal diet. Acidifier (g/kg): For, formic acid; Fum, fumaric acid; Na-fum, sodium fumarate. D, digestibility of non-acidified control diet; ΔD, %-unit change in the digestibility relative to the non-acidified control diet.

* Significantly different from the control diet ($P<0{\cdot}05$).

Table 8. Influence of dietary organic acids on the apparent ileal digestibility of crude protein and amino acids in growing pigs

Reference . . .	Mosenthin *et al.* 1992				Kemme *et al.* 1995		Mroz *et al.* 1997			
Diet/acidifier . . .	CPX	Pro (20)	CPX(s)	Pro (20)	CSM	Lac (30)	CPX	For (14)	Fum(18)	*n*-But(27)
	D (%)	ΔD	D (%)	ΔD	D (%)	ΔD	D (%)	ΔD	ΔD	ΔD
Crude protein	68·4	+2·9	65·1	+4·6	75·3	−1.0	69·0	+4·2*	+3·4	+5·2*
Essential amino acid										
Arginine	79·8	+5·3	77·5	+4·2	84·4	+1·3*	83·4	+2·0	+1·2	+2·2
Histidine	74·1	+7·2**	74·0	+4·9	80·9	+0·6	76·4	+4·5*	+4·2*	+4·8*
Isoleucine	68·1	+6·4	63·4	+5·5	78·8	+1·5*	75·4	+3·9*	+3·3*	+3·7*
Leucine	72·5	+6·5*	68·4	+4·1	84·1	+1·1	77·6	+3·2*	+2·9*	+3·5*
Lysine	75·0	+5·1	71·8	+4·6	78·4	+1·9**	77·5	+4·7*	+4·0*	+3·9*
Methionine	73·8	+3·1	68·5	+3·9	80·3	+1·4*	83·7	+2·3	+0·8	+2·0
Phenylalanine	76·8	+4·9*	73·9	+4·9	80·9	+1·1	77·0	+3·4*	+2·8	+3·7*
Threonine	63·9	+3·9	57·6	+5·5	69·8	+1·9*	70·4	+4·7*	+4·3*	+4·8
Tryptophan	—	—	—	—	71·2	+1·1	71·3	+4·5*	+4·2*	+5·3*
Valine	69·3	+6·5*	63·3	+7·1	77·1	+1·5*	—	—	—	—
Nonessential amino acid										
Alanine	65·3	+5·2	60·4	+6·6	79·1	+1·6*	68·3	+5·3*	+5·0*	+6·2*
Aspartate	68·5	+6·7	67·1	+5·1	76·4	+1·5*	71·2	+4·6*	+4·3*	+4·7*
Cystine	59·5	+4·1	55·8	+5·6	72·8	+0·1	65·2	+5·4*	+2·6	+6·5*
Glutamate	80·3	+5·6*	79·1	+6·1	84·4	+1·3*	77·5	+4·3*	+4·8*	+5·1*
Glycine	61·4	+4·9	56·5	+5·8	65·4	+2·1	57·7	+8·4*	+6·7*	+9·8*
Proline	—	—	—	—	82·4	+0·1	72·6	+3·9*	+4·6*	+4·3
Serine	70·6	+5·1	67·7	+7·1	79·0	+1·1	77·6	+3·1*	+3·0*	+3·4*
Tyrosine	78·2	+3·0	75·8	+3·0	81·3	+1·0	66·7	+2·6	−7.3*	+4·7

Diet: CPX, complex diet with several ingredients; s, supplemented with siliceous earth; CSM, maize−soyabean meal diet. Acidifier (g/kg): Pro, propionic acid; Lac, lactic acid; For, formic acid; Fum, fumaric acid; *n*-But, *n*-butyric acid. D, digestibility of non-acidified control diet; ΔD, %-unit change in the digestibility relative to the non-acidified control diet.

* Significantly different from the control diet ($P<0{\cdot}05$).

was noted with diets containing dried skim milk. On the other hand, Bolduan *et al.* (1988*b*) reported no effect of formic acid on the AID of crude protein. So far, only a few studies have been reported in the literature in which the effects of supplementation of organic acids or their salts on the AID of amino acids have been determined. The results of these studies are summarized in Tables 7 and 8.

According to Mosenthin *et al.* (1992), propionic acid supplementation of grower diets improved ($P < 0{\cdot}05$) the AID of several indispensable amino acids: arginine, histidine, leucine, phenylalanine and valine. Kemme *et al.* (1995) observed with growing pigs that dietary lactic acid supplementation improved ($P < 0{\cdot}05$) the AID of arginine, isoleucine, lysine, methionine, phenylalanine, threonine and valine. Recently, Mroz *et al.* (1997) reported that formic, fumaric and *n*-butyric acids improved the AID of several essential and nonessential amino acids by 3–6 % units ($P < 0{\cdot}05$). However, opposite results have been obtained with weaned piglets. Neither formic acid (Gabert *et al.* 1995), fumaric acid nor sodium fumarate (Gabert & Sauer, 1995) supplementation has been found to affect the AID of amino acids ($P > 0.05$). The diets used in studies with weaned piglets were either simple cereal–soyabean meal (Gabert & Sauer, 1995) or semipurified fishmeal diets (Gabert *et al.* 1995) whereas those used in studies with growing pigs were either simple maize–soyabean meal (Kemme *et al.* 1995) or complex by-product-based diets (Mosenthin *et al.* 1992; Mroz *et al.* 1997). Based on the available data, it is unclear whether differences in the effect on protein and amino acid digestibility are due to acidifier and its inclusion level, diet composition or the age of the pigs. It seems that when feedstuffs of high digestibility are used, a small improvement in the digestibility can be expected. So far, no information is available on the influences of dietary organic acids on endogenous protein excretion and true digestibility of amino acids.

Absorption and retention of minerals. Organic acids may improve the absorption of minerals, particularly Ca and P (Kirchgessner & Roth, 1980; Höhler & Pallauf, 1993; Jongbloed *et al.* 1995; Jongbloed & Jongbloed, 1996), although opposite results have also been reported (Radecki *et al.* 1988). All organic acids studied (citric, formic, fumaric, lactic, and propionic) seem to have a positive effect on Ca and P absorption. Jongbloed (1987) suggested that lowered intestinal pH increases the solubility of P, which may improve its absorption. However, the data on ileal pH (Table 3) do not support this assumption. The effects of organic acids on P digestibility are also dependent on the amount of phytase (*EC* 3.1.3.26), either intrinsic or of microbial origin, in the diet. Results of Jongbloed *et al.* (1995) and Jongbloed & Jongbloed (1996) indicate that organic acids may have an additional improving effect on the efficacy of phytase. A synergic effect of lactic acid and microbial phytase was reported in the study of Jongbloed *et al.* (1995). However, in the study of Radcliffe *et al.* (1998) no synergic effects were observed with citric-acid, and Jongbloed & Jongbloed (1996) showed it only for formic acid. Dietary organic acid supplementation improving P absorption and the efficacy of microbial phytase may thus contribute to reduced P excretion in the faeces.

Organic acids also appear to influence the retention of minerals. Kirchgessner & Roth (1980) reported that 20 g fumaric acid/kg diet in a weaner diet improved the balance of Ca, P, Mg and Zn by 14, 13, 21 and 43 % respectively. The magnitude of effect of organic acids depends on the type of diet and dietary mineral content. In diets with suboptimal levels of Zn, 15 g citric-acid/kg diet supplementation has reduced Zn deficiency symptoms (parakeratosis), but no significant effects on the apparent absorption and retention of Zn or other minerals (Ca, P, Mg, Fe, Cu, and Mn) has been found (Höhler & Pallauf, 1993, 1994).

Diet-induced changes in the blood acid–base status are important in affecting mineral retention. The retention of Ca and P can be lowered when animals are fed on strongly acidic diets, not owing to a reduction in intestinal Ca and P absorption but rather to a cell-mediated increase in bone resorption and associated changes in urinary mineral excretion (Abu Damir *et al.* 1991). Acidic diets can cause bone erosion due to the use of bone as a buffer for the body acid–base system (Petito & Evans, 1984). Chronic ingestion of NH_4Cl results in a significant loss of bone tissue, including both the organic and inorganic phases of the bone, due to increased resorption (Barzel & Jowsey, 1969). Also, Mroz *et al.* (1996) reported a significant reduction in retention of P when $CaCO_3$ was partly replaced with $CaCl_2$ or calcium benzoate in diets for growing gilts.

Straw *et al.* (1991) manipulated dietary pH from 5·4 to 6·7 with different mineral Na sources but observed no effect on bone development of weaned piglets. Kornegay *et al.* (1994) reported that the effect of acidification on bone stress values depended on dietary protein content. Increased stress values were observed with diets containing 160 g CP/kg compared with diets with 220 g CP/kg. The authors suggested that dietary protein can act as a buffer to modify the acidic potential. Radcliffe *et al.* (1998) observed no effect of citric-acid supplementation on bone shear force, but reported a tendency ($P < 0{\cdot}08$) for a linear increase in bone ash content with increasing level of acid in the diet.

Gastrointestinal microflora

Stress associated with weaning of piglets is known to disturb the intestinal microflora. It is well known that low luminal pH and rapid flow of digesta can markedly inhibit growth of microbes along the whole gastrointestinal tract (Maxwell & Stewart, 1995). It has also been shown that acidic conditions favour the growth of lactobacilli in the stomach (Fuller, 1977), which possibly inhibits the colonization and proliferation of *E. coli* by blocking the sites of adhesion or by producing lactic acid and other metabolites which lower the pH and inhibit *E. coli.*

Influence of microbial counts. Several reports have shown that the use of organic acids may reduce the coliform burden along the gastrointestinal tract (Cole *et al.* 1968; Scipioni *et al.* 1978; Thomlinson & Lawrence, 1981; Bolduan *et al.* 1988*b*; Mathew *et al.* 1991) and reduce scouring and piglet mortality. In segments of the small intestine, micro-organism counts of *Lactobacillus/Bifidobacterium*, *Eubacterium* and *Bacteroidaceae* were slightly decreased by the addition of 6–24 g formic acid/kg diet (Gedek *et al.* 1992*a*). The effect on *E. coli* counts in ileal digesta were not consistent, the highest counts being observed for diets supplemented with 18 g formic acid/kg diet. In the caecum and colon the counts of *Lactobacillus/Bifidobacterium* and *E. coli* were decreased ($P < 0{\cdot}05$) irrespective of the level of formic acid supplementation. Counts of *Lactobacillus/Bifidobacterium*, *Eubacterium spp.* and also the sum of the main flora in the duodenum, jejunum and ileum were significantly reduced by the addition of 18 g fumaric acid/kg diet (Gedek *et al.* 1992*b*). The influence of sodium formate was less profound. Fumaric acid also reduced the *Lactobacillus/Bifidobacterium* counts in the caecum and colon. *E. coli* counts were reduced in the jejunum by fumaric acid treatment, but not in other segments of the gastrointestinal tract.

In contrast, dietary organic acid supplementation (15 g citric or fumaric acid/kg diet) did not prevent the *E. coli* challenge from causing scouring and a growth lag in the studies of Risley *et al.* (1993). Organic acids had no effect on *E. coli* or *Lactobacillus* counts in different sections of the gastrointestinal tract. Clark & Batterham (1989) also failed to observe any effect of acidification on the incidence of scours. Risley *et al.* (1992) reported that 15 g citric or fumaric acid/kg diet had no appreciable effect on lactobacilli, clostridia or *E. coli* numbers in the stomach, jejunum, caecum, or colon of piglets. No *E. coli* were found in the stomach of piglets fed on diets supplemented with 10 g propionic acid or 3·5–12 g formic acid/kg diet (Bolduan *et al.* 1988*a*). Total bacteria contents were not significantly affected by organic acid supplementation.

Influence of fermentation patterns. Supplementation of 20 g propionic acid/kg diet did not affect the concentrations of NH_3, cadaverine or putrescine in ileal digesta ($P > 0{\cdot}05$), but decreased the concentration of cadaverine in caecal digesta (Mosenthin *et al.* 1992). With increasing formic acid dosage (6, 12, 18 and 24 g/kg diet), concentrations of volatile fatty acids (VFA) in the stomach and small intestine remained unchanged. In the caecum and colon butyric acid content was lowered. In the colon the concentrations of acetic and propionic acids and total VFA were diminished by adding 18 and 24 g formic acid/kg diet. In the whole large intestine the proportions of VFA were shifted to higher proportions of acetic acid largely at the expense of propionic and to a lesser extent butyric acids. Lactic acid concentration was decreased with increasing formic acid dosage, but no effect was observed in the stomach, caecum or colon (Roth *et al.* 1992*a*).

NH_3 content in the stomach was lowered ($P < 0{\cdot}05$) by increasing dosage of formic acid (6–24 g/kg diet), but was not significantly affected in other parts of the gastrointestinal tract (small intestine, caecum and colon; Eckel *et al.* 1992*b*). In the small intestine, concentrations of biogenic amines (cadaverine, putrescine, and spermidine) were not affected by formic acid supplementation, but were generally diminished in the caecum. In the stomach and small intestine, NH_3 content was significantly lowered by addition of 12·5 g formic acid/kg diet, whereas the buffer ($NaHCO_3$) increased NH_3 content (Eidelsburger *et al.* 1992*a*). Formic acid also decreased the lactic acid content in the stomach ($P < 0{\cdot}05$). In the caecum, contents of VFA were slightly lowered by formic acid and calcium formate supplementation, but were always increased with the addition of buffer. In caecum and colon contents, some VFA shifted to higher proportions of acetic acid at the cost of butyric acid. Neither fumaric acid (15 or 30 g/kg diet) nor sodium fumarate (15 g/kg diet) affected acetate or propionate concentrations in ileal digesta. For diets supplemented with fumaric acid, concentrations of butyrate increased quadratically ($P < 0{\cdot}05$) with increased acid dose (Gabert & Sauer, 1995). Formic acid (10 g/kg diet) did not affect VFA concentrations in ileal digesta (Gabert *et al.* 1995).

Pancreatic enzyme secretion

A series of hormonal mechanisms via the autonomic nervous system are set in action by the ingestion of food, which activates and controls pancreatic secretion of water, electrolytes and digestive enzymes (Solomon, 1994). Some results indicate that short-chain fatty acids have a stimulatory effect on both endocrine and exocrine pancreatic secretions in pigs (Harada *et al.* 1986; Sano *et al.* 1995), as well as in sheep (Harada & Kato, 1983) and calves (Kato *et al.* 1989).

Using anaesthetized piglets, Harada *et al.* (1986) observed that pancreatic secretory responses induced by intraduodenal instillation of HCl or lactic acid were dependent on pH. For solutions of HCl, the threshold existed around pH 1·3, and around pH 3·8 in the case of lactic acid. Above these pH values secretin was not released in amounts sufficient to stimulate pancreatic exocrine secretion. Pancreatic exocrine responses induced by other monocarboxylic acid solutions (250 mM) of pH 2·0 were ranked as: formic acid > lactic acid > pyruvic acid > acetic acid > butyric acid > propionic acid. In anaesthetized sheep, pancreatic juice flow, amylase, and protein outputs rapidly increased after intrajugular injection of acetate, propionate, and butyrate. Secretory response to butyrate was significantly greater than that observed with propionate or acetate. Rapid intravenous injection of butyrate (625 μmol/kg BW) caused a 13-fold rise in the juice flow, 26-fold increase in protein output, and 37-fold increase in amylase output above basal levels within 5 min, which declined to basal levels over a period of 30 min (Harada & Kato, 1983). Similarly, with 2-week-old calves, which were given only whole milk and milk replacers and therefore considered as nonruminants, intravenous injections of sodium acetate, propionate or butyrate (625 mmol/kg BW) stimulated pancreatic juice secretion and protein and amylase output (Kato *et al.* 1989). Responses increased with increasing fatty acid chain length, butyrate being the most effective stimulant.

Intestinal acidification either with HCl or monocarboxylic acids elevates serum secretin content in pigs (Harada *et al.* 1986, 1988). Both pancreatic exocrine secretion and biliary excretion are stimulated via the release of secretin (Harada *et al.* 1988). In an experiment with growing gilts of 25 kg BW, an intravenously injected supraphysiological dose (2·5 mmol/kg BW) of *n*-butyrate increased plasma glucagon concentrations ($P < 0{\cdot}05$) following an initial temporary decrease ($P<0{\cdot}05$). A similar tendency was observed after acetate or propionate injection. However, plasma insulin concentrations were not influenced by injections of VFA. Results suggest that supraphysiological doses of acetate, propionate or *n*-butyrate may stimulate plasma glucagon responses in growing piglets (Sano *et al.* 1995).

Gut morphology

At weaning the small intestine of the piglet generally undergoes a reduction in villous height and an increase in crypt depth, changes which are associated with decreased absorption capacity (Cera *et al.* 1988; Nabuurs, 1995; Pluske *et al.* 1996). Similar changes are observed in the epithelium of the small intestine with a reduction in voluntary food intake (Pluske *et al.* 1996) and postweaning diarrhoea (Nabuurs, 1995). Changes in gut morphology are important as they can reduce growth and prolong the time pigs take to reach slaughter weight. According to Pluske *et al.* (1996), weight gain of weaned piglets is positively correlated with villous height.

Villous shortening and crypt deepening after weaning can be partly prevented by giving piglets supplementary feed during suckling (Nabuurs, 1995) or by feeding weaned piglets with a liquid milk diet (Pluske *et al.* 1996). So far, little is known about the influence of dietary acidification on pig gut morphology. Gálfi & Bokori (1990) observed that 1·7 g/kg sodium butyrate in the diet resulted in a substantial increase in the number of cells (33·5 %) constituting microvilli, and in the length of microvilli (30·1 %) in the ileum of growing pigs. Pigs also grew faster than in the control group. Whether other dietary acidifiers have similar effects is not known. However, it is well known that short-chain fatty acids (acetic, propionic and *n*-butyric acid) produced by microbial fermentation of carbohydrates stimulate epithelial cell proliferation (Lupton & Kurtz, 1993; Sakata *et al.* 1995; Marsman & McBurney, 1996). The strength of the effect is in the order *n*-butyric > propionic > acetic acid (Sakata, 1987). Increased epithelial cell proliferation has also been observed when short-chain fatty acids have been given orally or provided by intravenous or gastrointestinal infusions (Frankel *et al.* 1994; Sakata *et al.* 1995), as dietary organic acids can influence fermentation patterns in the small intestine, and may indirectly influence intestinal morphology.

Intermediary metabolism

Kirchgessner & Roth (1988) have proposed that organic acids may stimulate intermediary metabolism resulting in improved energy or protein/amino acid utilization. Grassmann *et al.*

(1992) found that formic acid addition to weaner diets increased the activities of α-ketoglutaric dehydrogenase (*EC* 1.2.4.2) and glutamate–pyruvate transaminase (*EC* 2.6.1.15), when diets were supplemented with 18 or 24 g formic acid/kg. Imoto & Namioka (1983) fed acetate in the form of triacetin to growing pigs, at 0, 5 and 10 % of metabolizable energy intake. Weight gain and N retention showed a linear increase ($P < 0{\cdot}001$) with increasing levels of acetate. The efficiency of acetate utilization for BW gain was 0·90 g/g acetate, and the mean N-sparing effect of acetate was 32·9 mg N/g acetate. A linear increase was observed in the weights of liver, heart and femoral muscle ($P < 0{\cdot}01$), and in their protein ($P < 0{\cdot}01$) and RNA ($P < 0{\cdot}05$) content with increased acetate intake. However, the total DNA content did not change, indicating that acetate had no effect on the number of nuclei or the number of cells in the tissues. However, in practical conditions supplementation of diets with acetic acid has not resulted in increased average daily gain or improved gain : feed ratio (Zhang *et al.* 1986; Roth & Kirchgessner, 1988).

Tschierschwitz *et al.* (1982) and Grassmann & Klasna (1986) investigated the effects of dietary fumaric acid supplementation on intermediary metabolism in the rat liver. In both studies no effect of fumaric acid on the activities of enzymes in the citric-acid cycle was found. However, Tschierschwitz *et al.* (1982) observed increased activity of aspartate transferase (*EC* 2.6.1.1) and succinate dehydrogenase (*EC* 1.3.5.1) with the addition of fumaric acid to rat diets. Grassmann & Klasna (1986) reported that fumarase (*EC* 4.2.1.2) activity in the cytosolic fraction was increased by fumaric acid supplementation. It also increased liver transaminase (glutamate dehydrogenase (*EC* 1.4.1.2), glutamate–oxaloacetate transaminase (*EC* 2.6.1) and glutamate–pyruvate transaminase) activities, which may indicate increased synthesis of nonessential amino acids.

Grassmann & Kirchgessner (1979) and Grassmann & Klasna (1986) measured the effects of supplementation of diets with citric-acid on intermediary metabolism in the rat liver. There was no effect of citric-acid supplementation on the activities of enzymes in the citric-acid cycle. However, succinate dehydrogenase activity was increased in one study and decreased in another. Grassmann & Kirchgessner (1979) reported that citric-acid supplementation did not affect the activities of liver transaminases. However, Grassmann & Klasna (1986) reported that citric-acid supplementation increased liver glutamate dehydrogenase, glutamate–oxaloacetate transaminase and glutamate–pyruvate transaminase activities. An increase in transaminase activities may indicate that the C skeleton of citrate is being used to synthesize nonessential amino acids.

Concluding remarks and future perspectives

Organic acids and their salts have been established as potential alternatives to prophylactic use of in-feed antibiotics in order to improve the performance of weaned piglets, fattening pigs and reproductive sows. However, their effect on performance was found often to vary and more specific studies are necessary to elucidate an explanation. Particularly with young piglets, more attention should be paid to maintaining continuous feed intake before and after weaning, and including organic acids, as it is a prerequisite of good performance. Exact modes of action of organic acids in particular sections of the gastrointestinal tract still remain unresolved in the context of inconsistencies concerning digestion and absorption of particular organic and inorganic nutrients. From a very limited number of experiments it seems that organic acids improve the apparent ileal digestibility of amino acids in growing pigs, but not in weaned piglets. More data are needed, with studies also using adult sows. So far, no information is available on the influences of organic acids on endogenous protein and amino acid losses and on true digestibility of feed protein and amino acids. Organic acids may also influence gut morphology, increasing villous height and therefore the absorptive capacity, which could contribute to improved protein, energy and/or mineral absorption.

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