The effects of feed additive, selenium source, polyphenol, lysine level, and sow lactation feeder type on pigs

by

Zhong-Xing Rao

B.S., National Chung Hsing University, Taiwan, 2017
M.S., Kansas State University, 2020

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

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Abstract

Chapter 1 is a review paper that summarized the effects of 14 feed additive categories on grow-finish pig growth performance and carcass characteristics. The summarized data suggests that most results were positive for each feed additive; however, the magnitude of improvement varied, and most were not statistically significant. For ADG, DFM, Cu, L-carnitine, and multi-enzymes showed relatively large positive effects (> 2.1% improvement) across a reasonable number of articles. Acidifiers, betaine, CLA, multi-enzymes, DFM, L-carnitine, and yeasts showed relatively large positive effects (> 2.5% improvement) on improving G:F. Moreover, except for betaine, Cr, CLA, and L-carnitine, most feed additives showed little and non-significant effects on BF thickness (< 1.7% improvement). Chapter 2 utilized a total of 3,888 nursery pigs to evaluate selenium source on nursery pig growth performance, serum and tissue selenium concentrations, and serum antioxidant status. The results suggested that, compared to sodium selenite and selenium yeast, hydroxy-selenomethionine (OH-SeMet) had greater bioavailability as indicated by increased serum and tissue selenium concentration; however, antioxidant status was similar between treatments and OH-SeMet tended to reduce growth performance compared with pigs fed sodium selenite. Chapter 3 utilized a total of 300 nursery pigs to evaluate the effects of using polyphenols as a partial replacement for vitamin E in nursery pig diets. Increasing vitamin E equivalence improved feed efficiency which may be related to the improved antioxidant status. Providing additional vitamin E equivalence above the basal vitamin E requirement through either vitamin E or polyphenol showed similar benefits. Thus, the polyphenol used in this study can be used as an effective replacement for vitamin E supplemented above the basal requirement. Chapter 4 utilized a total of 702 90-kg finishing pigs to evaluate nutritional strategies for slowing growth rate then inducing compensatory growth. We found feeding Lys-restricted diets reduced the ADG and G:F of finishing pigs. Moreover, compensatory growth can be induced in Lys-restricted finishing pigs, but the duration of restriction and recovery influences the magnitude of compensatory growth. Chapter 5 utilized a total of 600 sows to evaluate sow feeder type and drip cooling on sow bodyweight, litter performance, and feeder cleaning

criteria in a hot and humid environment. We determined that sows used SowMax feeders had reduced feed disappearance with no effects on sow and litter performance compared to a PVC tube feeder, and drip cooling improved sow and litter performance during summer in a hot and humid environment.

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Chapter 1 - Effects of various feed additives on finishing pig growth performance and carcass characteristics: A review.

Abstract

Feed additives have shown benefits throughout the literature in improving grow–finish pigs' growth performance and carcass characteristics. However, the results have not been well summarized. Therefore, this review summarizes the available research (402 articles) on 14 feed additive categories fed to grow–finish pigs. The categories were acidifiers, betaine, Cr, conjugated linoleic acids, Cu, direct-fed microbials, carbohydrases, proteases, phytases, multi-enzymes, essential oils, L-carnitine, yeasts, and Zn. Qualified articles were collected and selected based on inclusion and exclusion criteria from online databases. The percentage difference for each response variable between the treatment and control group was calculated and summarized. Most results were positive for each feed additive; however, the magnitude of improvement varied, and most were not statistically significant. For ADG, DFM, Cu, L-carnitine, and multi-enzymes showed relatively large positive effects (>2.1% improvement) across a reasonable number of articles. Acidifiers, betaine, CLA, multi-enzymes, DFM, L-carnitine, and yeasts showed relatively large positive effects (>2.5% improvement) on improving G:F. Moreover, except for betaine, Cr, CLA, and L-carnitine, most feed additives showed little and non-significant effects on BF thickness (<1.7% improvement). This review provides a descriptive analysis for commonly used feed additives in the hope of better understanding feed additives' effects on grow–finish pigs.

Introduction

Growth performance, especially feed efficiency, becomes increasingly important for achieving sustainable and competitive pig production as feed prices and environmental concerns rise. A pig consumes most of the feed in its lifetime during the grow–finish phase. Moreover, feed efficiency decreases as the pig's weight increases because of the increasing maintenance requirement [1]. One of the potential methods to improve efficiency is including feed additives that have the potential to enhance energy utilization or reduce maintenance requirements. Several feed additives have been widely used in the swine feed industry. These feed additives provide different mechanisms of action that can potentially improve growth performance without negatively affecting the ADG. Feed additives (acidifiers, EO, DFM, yeasts, Cu, and Zn) that show antibacterial and immune-promoting properties have been added to diets to control pathogens and maintain a balanced microbiota in the gastrointestinal tract [2–7]. Betaine, Cr, CLA, and L-carnitine are added to diets for their beneficial effects on energy and lipid metabolism [8–11]. Moreover, exogenous enzymes, such as carbohydrases, proteases, and phytases, are added to improve nutrient digestibility coefficients and for the potential positive effects on gastrointestinal health and immune functions [12,13]. Even though the mechanisms of these feed additives seem promising, the effects on finishing pigs' growth performance are variable throughout the literature. This variability in response may be caused by the developmental status (weaned pigs vs. grow–finish pigs) of the pig, diet compositions [14,15], and environmental factors [16]. Moreover, because carcass characteristics are important economic criteria, this literature review also discusses the effects of these feed additives on backfat, percentage lean, and loin muscle criteria. Therefore, this literature review summarizes the available results of feed additive research to help determine which feed additives have the

greatest and most consistent potential to improve growth performance and carcass characteristics of finishing pigs.

Material and Methods

Data Source

The online article databases used for this literature review were the International System for Agricultural Science and Technology (AGRIS), Centre for Agriculture and Bioscience International (CABI; CAB Direct), Pork Checkoff research, PubMed, and Scopus. Articles were identified using the following terms: pig, swine, barrow, or gilt with the name of the feed additive of interest. The feed additives of interest were acidifiers, betaine, Cr, conjugated linoleic acid (CLA), Cu, direct-fed microbials (DFM), carbohydrases, proteases, phytases, multi-enzymes (combinations of carbohydrases, proteases, or phytases), essential oils (EO), L-carnitine, yeasts, and Zn. This literature review did not include ractopamine (RAC) because of the global trend of removing RAC in grow–finish pig diets. The language of the articles was limited to English, and the article types were limited to research articles and university research reports. There is no restriction on the publication years for selecting articles and the years of the selected papers ranged from 1957 to 2022.

Inclusion and Exclusion Criteria

Research articles were included if they met the following criteria: (1) the study was an original randomized controlled in vivo study; (2) the study had a control group fed a basal diet without the feed additive of interest and treatment groups with the feed additive added to the basal diet with other nutrient values similar to the control; (3) control and treatment pigs had to have a similar starting live body weight over 7 kg (post-weaning), and an end point above 80 kg live body weight with an identical (fix-time study) or similar (fix-weight study) experimental

period; (4) the study reported either the growth performance (BW, ADG, ADFI, G:F), carcass characteristics [e.g., carcass weight, percent carcass yield, backfat thickness (BF), loin muscle area (LMA), loin muscle depth (LD), percentage lean] or both criteria with statistical analysis. The exclusion criteria were (1) duplicate search results; (2) data duplication between different research articles; (3) the article did not provide numeric values of the results; or (4) the original full text of the article could not be found. With the inclusion and exclusion criteria, a total of 402 research articles were selected for the 14 different feed additives frequently used in grow–finish pig diets.

Data Extraction and Analysis

Article information, treatment design, response variables, and statistical results were extracted from the selected articles. Article information included authors, published journal, article type, title, published year, and the location of the study. Treatment design included the feed additive used, the form of the additive, feed additive inclusion level, duration of the study, the first 2 major ingredients in the diet (e.g., corn–soybean meal, barley–wheat), pig breed, sex, housing type (individual or group pen), and initial BW. Response variables included final BW, ADG, ADFI, G:F, carcass weight, BF, percentage lean, and LMA/LD. Statistical results included the standard error of the mean (SEM) of the response of interest and the p-value of the response of interest compared to the control. Because the reported values of BF vary on the sampling locations, if the location was reported, the priority sequence of extracted value was average BF, 10th rib BF, last rib BF, loin BF, and other locations. If the location was not reported, the value was extracted as listed in the article regardless of the location. Because of the similarity between LMA and LD, both values were extracted for the same category. If both values were reported, LMA was prioritized over LD. The extracted data of each treatment group was entered into the database as a row of data.

The relative difference in the response between the treatment group and the control was calculated as the percentage of difference and defined as a comparison in this literature review. The determination of significance, p-value, and response value were based on the study design and statistical analysis. The significance of each comparison was categorized as significant if the reported p-value was below or at 0.05 ($p \leq 0.05$). The comparisons were categorized as tendency if the reported p-value was between 0.05 and 0.10 ($0.05 < p \leq 0.10$) and as non-significant if the reported p-value was above 0.10 ($p > 0.10$). For studies that only reported whether the p-value was below or above 0.05 and it cannot be determined whether there was a tendency ($0.05 < p \leq 0.10$), the comparisons were categorized as significant ($p \leq 0.05$) or non-significant ($p > 0.10$). For studies that utilized polynomial contrasts, if the polynomial p-value was significant or indicated a tendency, the same p-value was assigned to all comparisons in the polynomial contrast despite the numeric difference in the response, to reflect the general effect of adding the additive on finding a significant difference. If the polynomial p-value was not significant, the determination of the p-value was based on the p-value of the pairwise comparison if available. If the pairwise comparison was unavailable, the non-significant polynomial p-value was used for all comparisons. For studies with factorial treatment structure, the combined means and main effect p-values were extracted if there was no significant interactive effect, regardless of the other factors. If there was a significant or a tendency of interactive effect of either variable, all possible comparisons were extracted separately for all variables of interest. However, if the other factor in the basal diets was the addition of ractopamine, the data was not extracted. For each response of the feed additive, the number of the extracted comparisons was counted, and the percentage difference was used to summarize the average positive, neutral, and negative effects of the feed additives at each significant level as a descriptive statistical analysis.

Responses to each feed additive are summarized for the different response criteria (growth performance and carcass characteristics) based on the number of comparisons, magnitude of improvement, and statistical significance levels in Tables 1.1–1.5. Moreover, the distribution of results for each feed additive was summarized by the significance level and direction of improvement in Figures 1.1–1.5. Because of the large number of studies included in the review, the detailed summaries of each additive category, the extracted results of every comparison, and citations were reported in Appendix A as a supplemental paper (Tables A.1–A.22).

Table 1.1. Summary of the effects of feed additives on grow–finish pig ADG [1,3].

Item	Comparisons, n	Difference, %[2]	Positive			Neutral	Negative		
			Sig.	Tendency	NS.		NS.	Tendency	Sig.
Acidifiers	68	1.7	18 (5.8)	0	31 (3.4)	0	15 (-3.4)	0	4 (-10.8)
Essential oils	20	5.8	10 (9.9)	0	6 (3.8)	1	3 (-1.7)	0	0
DFM	71	3.3	25 (6.3)	2 (3.9)	30 (3.6)	0	13 (-2.3)	0	1 (-5.8)
Yeasts	36	1.6	9 (5.6)	0	16 (3.2)	0	11 (-4.1)	0	0
Copper	155	2.5	30 (6.2)	3 (4.1)	81 (3.8)	7	33 (-3.4)	0	1 (-0.1)
Zinc	30	0.6	1 (18.7)	1 (1.1)	12 (4.0)	4	11 (-3.2)	0	1 (-14.4)
Betaine	37	1.3	7 (10.6)	1 (4.3)	10 (2.4)	2	15 (-3.3)	0	2 (-2.8)
Chromium	139	1.1	14 (8.9)	4 (4.6)	51 (3.6)	10	48 (-2.2)	5 (-4.1)	7 (-7.2)
CLA	62	1.2	5 (7.2)	1 (3.6)	34 (3.7)	2	17 (-4.1)	0	3 (-7.8)
L-carnitine	24	2.1	2 (3.3)	4 (3.1)	13 (3.4)	1	3 (-2.6)	0	1 (-4.8)
Carbohydrases	87	1.3	15 (5.3)	5 (4.0)	35 (2.9)	4	24 (-3.3)	0	4 (-2.7)
Proteases	23	0.6	3 (5.2)	4 (3.2)	9 (2.1)	0	5 (-3.7)	0	2 (-7.6)
Phytases	24	1.1	3 (6.8)	0	12 (2.6)	1	8 (-3.0)	0	0
Multi-enzymes	29	3.1	10 (7.9)	0	10 (2.9)	1	8 (-2.3)	0	0

[1]Significant (Sig.; $p \leq 0.05$), tendency ($0.05 < p \leq 0.10$), and non-significant (NS.; $p > 0.10$). [2]Average of the % of difference of all the comparisons. [3]Number outside of the parentheses represents the number of comparisons. Number inside the parentheses represents the average of the percentage of difference of these comparisons.

Table 1.2. Summary of the effects of feed additives on grow–finish pig G:F [1,3].

Item	Comparisons, n	Difference, %[2]	Positive			Neutral	Negative		
			Sig.	Tendency	NS.		NS.	Tendency	Sig.
Acidifiers	65	3.1	13 (6.4)	0	40 (3.8)	2	9 (-3.1)	0	1 (-9.7)
Essential oils	17	5.8	7 (10.9)	1 (4.5)	6 (3.5)	1	2 (-1.5)	0	0
DFM	66	3.3	18 (6.1)	3 (3.0)	32 (3.9)	2	11 (-2.2)	0	0
Yeasts	33	2.7	10 (7.8)	0	12 (3.9)	1	10 (-3.6)	0	0
Copper	149	1.8	30 (5.1)	3 (1.0)	71 (3.1)	6	37 (-2.7)	0	2 (-3.7)
Zinc	30	1.2	0	4 (1.2)	14 (4.2)	1	11 (-2.6)	0	0
Betaine	35	2.7	5 (13.2)	0	18 (2.7)	2	9 (-2.3)	0	1 (-0.4)
Chromium	138	1.0	14 (5.2)	0	60 (3.1)	16	41 (-2.1)	0	7 (-4.3)
CLA	57	3.5	13 (4.5)	6 (8.8)	24 (4.6)	4	9 (-2.3)	0	1 (-2.8)
L-carnitine	24	2.5	1 (2.9)	3 (3.7)	13 (4.4)	2	5 (-2.0)	0	0
Carbohydrases	84	1.7	8 (8.5)	2 (5.9)	46 (2.9)	9	19 (-3.8)	0	0
Proteases	22	1.8	7 (4.9)	1 (7.6)	5 (2.2)	2	7 (-2.0)	0	0
Phytases	24	1.1	2 (5.7)	1 (2.9)	13 (2.3)	1	7 (-2.5)	0	0
Multi-enzymes	29	3.3	10 (9.0)	0	12 (1.8)	2	5 (-3.3)	0	0

[1]Significant (Sig.; $p \leq 0.05$), tendency ($0.05 < p \leq 0.10$), and non-significant (NS.; $p > 0.10$). [2]Average of the % of difference of all the comparisons. [3]Number outside of the parentheses represents the number of comparisons. Number inside the parentheses represents the average of the percentage of difference of these comparisons.

Table 1.3. Summary of the effects of feed additives on grow–finish pig BF [1,3].

Item	Comparisons, n	Difference, %[2]	Positive			Neutral	Negative		
			Sig.	Tendency	NS.		NS.	Tendency	Sig.
Acidifiers	24	-0.6	0	0	14 (2.6)	2	5 (-3.2)	0	3 (-12)
Essential oils	14	-2.7	0	0	5 (3.7)	0	6 (-5.5)	0	3 (-2.7)
DFM	21	-1.5	1 (16.8)	0	6 (7.1)	0	9 (-6.3)	3 (-2.9)	2 (-13.1)
Yeasts	21	-3.1	0	0	12 (4.1)	1	8 (-14.4)	0	0
Copper	73	-1.4	0	0	24 (3.5)	9	36 (-4.1)	1 (-5.4)	3 (-10.3)
Zinc	19	-0.6	1 (13.1)	0	5 (1.3)	2	11 (-2.9)	0	0
Betaine	32	-1.7	0	0	13 (2)	0	16 (-2.9)	0	3 (-10.7)
Chromium	133	-3.9	2 (8)	5 (6.3)	42 (4.2)	2	53 (-6.4)	7 (-12.4)	22 (-14.4)
CLA	59	-7.0	0	0	14 (4)	2	16 (-6.1)	5 (-6.5)	22 (-15.4)
L-carnitine	22	-3.4	3 (4)	2 (1.4)	1 (1.9)	1	6 (-5.7)	7 (-4.8)	2 (-12.5)
Carbohydrases	57	-0.4	2 (4.1)	1 (4.8)	18 (4)	7	29 (-3.7)	0	0
Proteases	13	-0.1	0	3 (3.7)	3 (4.5)	1	6 (-4.4)	0	0
Phytases	14	-0.2	1 (8.3)	0	6 (1.7)	2	5 (-4.2)	0	0
Multi-enzymes	12	2.8	0	0	6 (10.4)	0	5 (-3.8)	0	1 (-10.2)

[1]Significant (Sig.; $p \leq 0.05$), tendency ($0.05 < p \leq 0.10$), and non-significant (NS.; $p > 0.10$). [2]Average of the % of difference of all the comparisons. [3]Number outside of the parentheses represents the number of comparisons. Number inside the parentheses represents the average of the percentage of difference of these comparisons.

Table 1.4. Summary of the effects of feed additives on grow–finish pig percentage lean [1,3].

Item	Comparisons, n	Difference, %[2]	Positive			Neutral	Negative		
			Sig.	Tendency	NS.		NS.	Tendency	Sig.
Acidifiers	24	-0.5	0	0	9 (0.9)	0	15 (-1.4)	0	0
Essential oils	9	0.9	3 (2.5)	0	3 (1.2)	1	2 (-1.5)	0	0
DFM	13	1.0	0	1 (1.8)	9 (1.8)	0	3 (-1.8)	0	0
Yeasts	8	1.0	0	3 (0.8)	2 (4.9)	0	2 (-1.3)	1 (-1.2)	0
Copper	25	1.6	2 (1.1)	0	16 (2.8)	0	7 (-1.1)	0	0
Zinc	14	0.9	0	0	12 (1.1)	1	1 (-0.4)	0	0
Betaine	25	2.0	1 (5.2)	0	15 (3.6)	1	8 (-1.2)	0	0
Chromium	105	1.6	20 (6.6)	1 (5)	43 (1.9)	3	36 (-1.2)	0	2 (-4.1)
CLA	37	2.6	14 (4.9)	0	16 (1.9)	0	7 (-0.6)	0	0
L-carnitine	20	1.1	4 (3.8)	2 (1.5)	7 (1.5)	1	3 (-0.7)	0	3 (-1.3)
Carbohydrases	55	0.3	1 (5.6)	0	28 (1.1)	4	20 (-0.8)	0	2 (-0.7)
Proteases	13	0.0	0	0	6 (1.1)	1	6 (-1.1)	0	0
Phytases	9	0.0	0	0	4 (0.6)	0	5 (-0.5)	0	0
Multi-enzymes	9	0.7	1 (4.4)	0	6 (0.6)	0	2 (-0.9)	0	0

[1]Significant (Sig.; $p \leq 0.05$), tendency ($0.05 < p \leq 0.10$), and non-significant (NS.; $p > 0.10$). [2]Average of the % of difference of all the comparisons. [3]Number outside of the parentheses represents the number of comparisons. Number inside the parentheses represents the average of the percentage of difference of these comparisons.

Table 1.5. Summary of the effects of feed additives on grow–finish pig longissimus muscle area/loin depth [1,3].

Item	Comparisons, n	Difference, %[2]	Positive			Neutral	Negative		
			Sig.	Tendency	NS.		NS.	Tendency	Sig.
Acidifiers	11	1.6	2 (6.3)	0	7 (2.6)	0	2 (-6.9)	0	0
Essential oils	10	1.9	3 (7.1)	0	4 (1)	0	3 (-2.3)	0	0
DFM	19	1.5	1 (10.9)	0	14 (2)	1	3 (-3.4)	0	0
Yeasts	17	1.4	0	0	10 (3.6)	0	7 (-1.9)	0	0
Copper	62	2.3	5 (4.4)	0	43 (3.4)	2	11 (-1.4)	0	1 (-7.5)
Zinc	15	0.2	0	0	11 (0.9)	0	4 (-1.5)	0	0
Betaine	24	-0.2	0	1 (6.3)	10 (1.9)	0	10 (-2.2)	0	3 (-2.3)
Chromium	125	3.1	23 (13.9)	0	61 (3.2)	2	38 (-3)	0	1 (-11.6)
CLA	38	0.9	6 (7.6)	1 (3.7)	14 (3)	0	15 (-3)	1 (-4.8)	1 (-5.9)
L-carnitine	21	2.4	1 (6.3)	0	13 (4.4)	1	6 (-2.3)	0	0
Carbohydrases	38	1.1	0	0	20 (3.3)	1	17 (-1.5)	0	0
Proteases	9	-2	0	0	3 (2.4)	0	6 (-4.1)	0	0
Phytases	11	-1.4	0	0	7 (1.7)	0	4 (-6.9)	0	0
Multi-enzymes	9	0.3	1 (11.3)	0	3 (1.8)	0	5 (-2.8)	0	0

[1]Significant (Sig.; $p \leq 0.05$), tendency ($0.05 < p \leq 0.10$), and non-significant (NS.; $p > 0.10$). [2]Average of the % of difference of all the comparisons. [3]Number outside of the parentheses represents the number of comparisons. Number inside the parentheses represents the average of the percentage of difference of these comparisons.

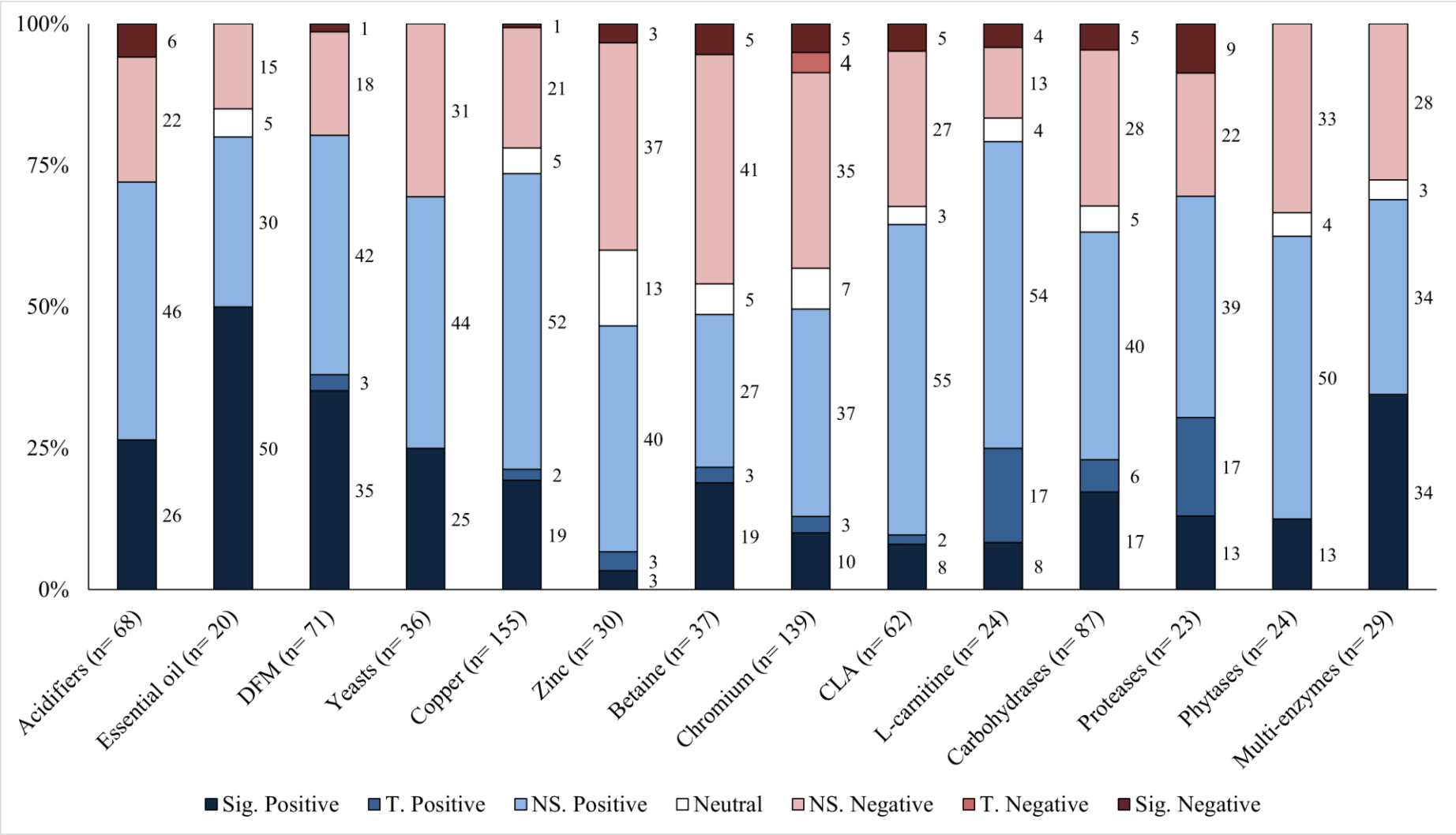

Figure 1.1. The distribution of results for various feed additives on ADG by significance level and direction.

The comparison was significant (Sig.) if $p \leq 0.05$, had a tendency (T.) if $0.05 < p \leq 0.10$, and was non-significant (NS.) if $p > 0.10$.

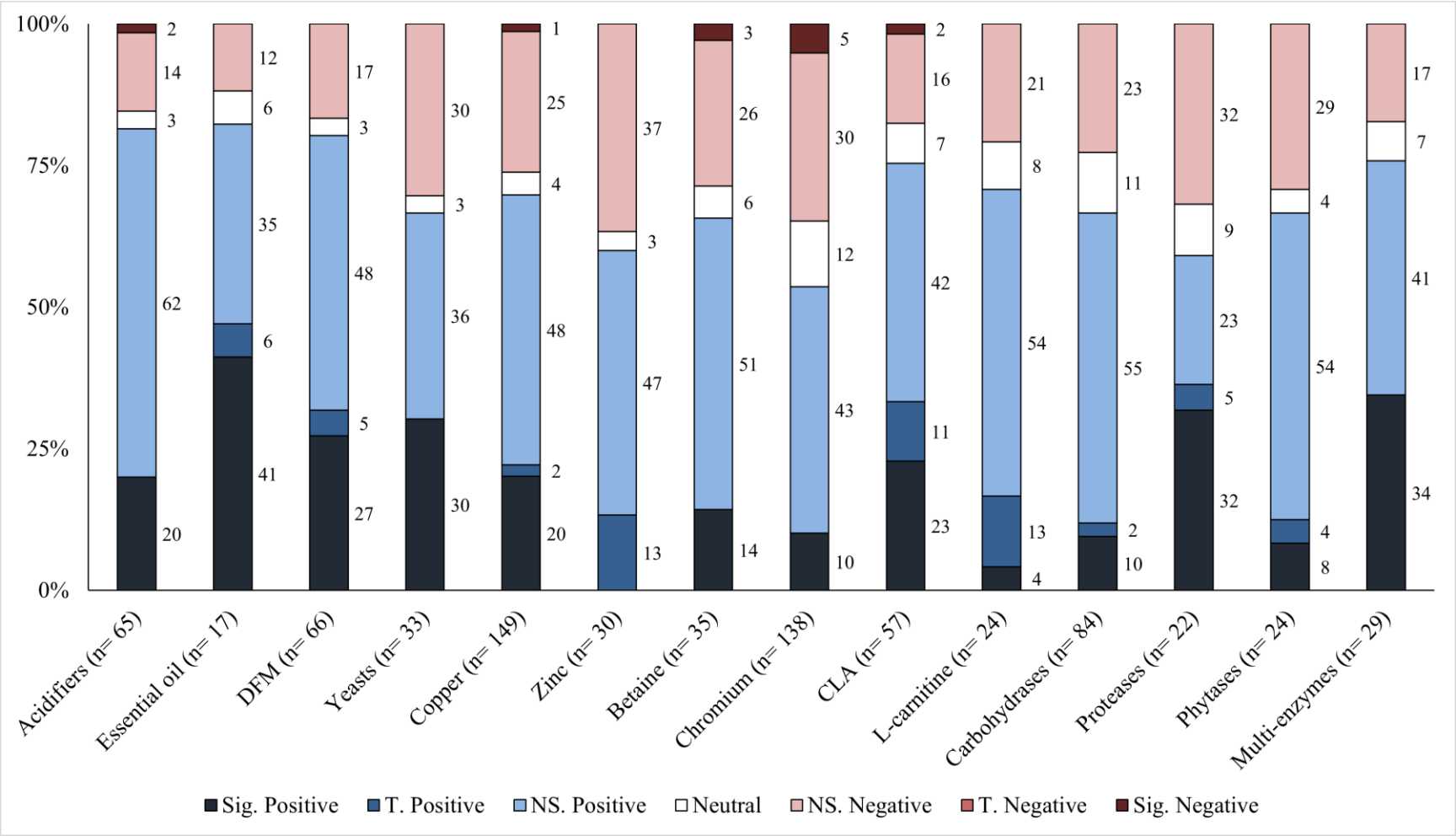

Figure 1.2. The distribution of results for various feed additives on G:F by significance level and direction.

The comparison was significant (Sig.) if $p \leq 0.05$, had a tendency (T.) if $0.05 < p \leq 0.10$, and was non-significant (NS.) if $p > 0.10$

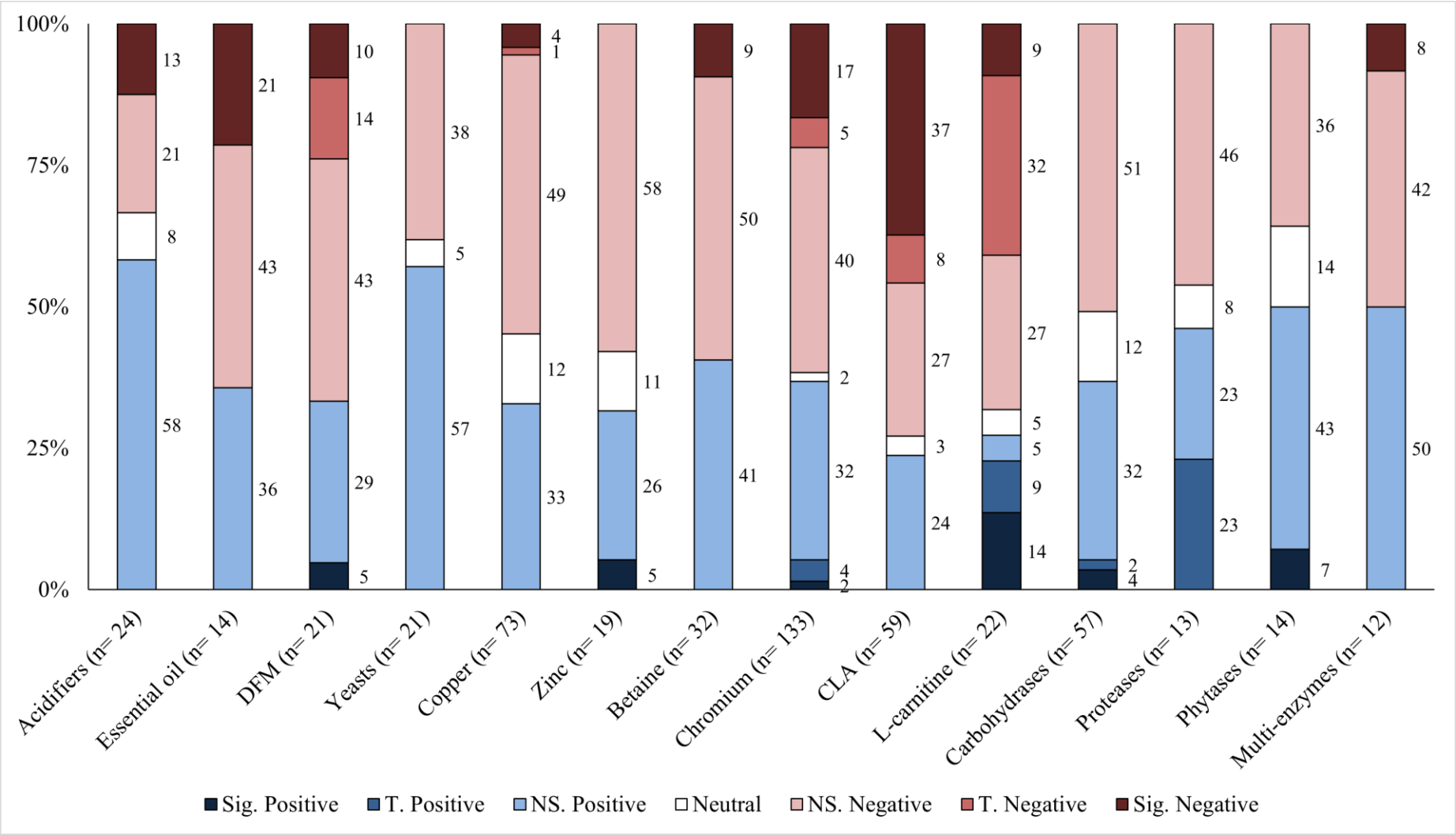

Figure 1.3. The distribution of results for various feed additives on BF by significance level and direction.

The comparison was significant (Sig.) if $p \leq 0.05$, had a tendency (T.) if $0.05 < p \leq 0.10$, and was non-significant (NS.) if $p > 0.10$.

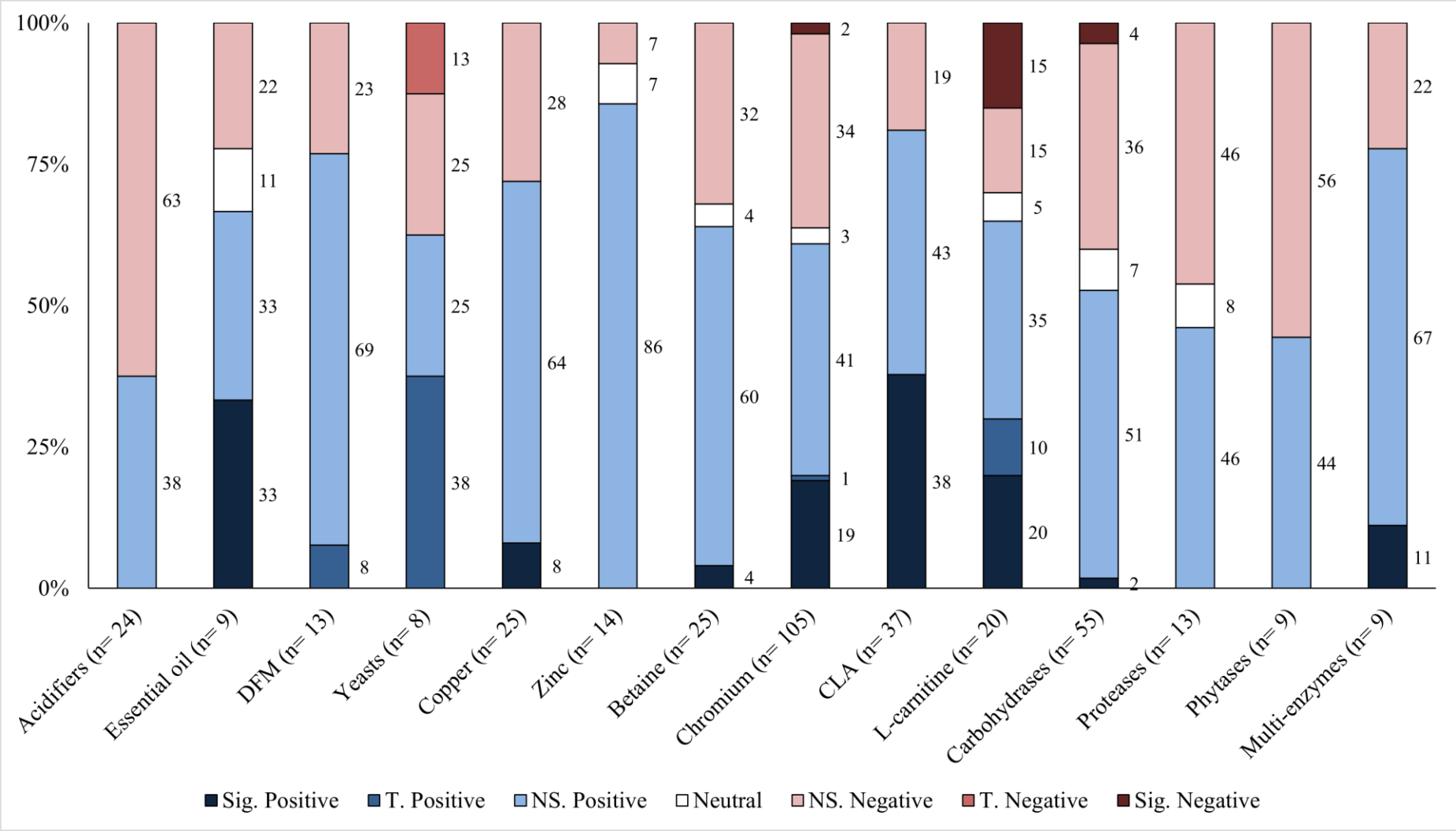

Figure 1.4. The distribution of results for various feed additives on percentage lean by significance level and direction.

The comparison was significant (Sig.) if $p \leq 0.05$, had a tendency (T.) if $0.05 < p \leq 0.10$, and was non-significant (NS.) if $p > 0.10$.

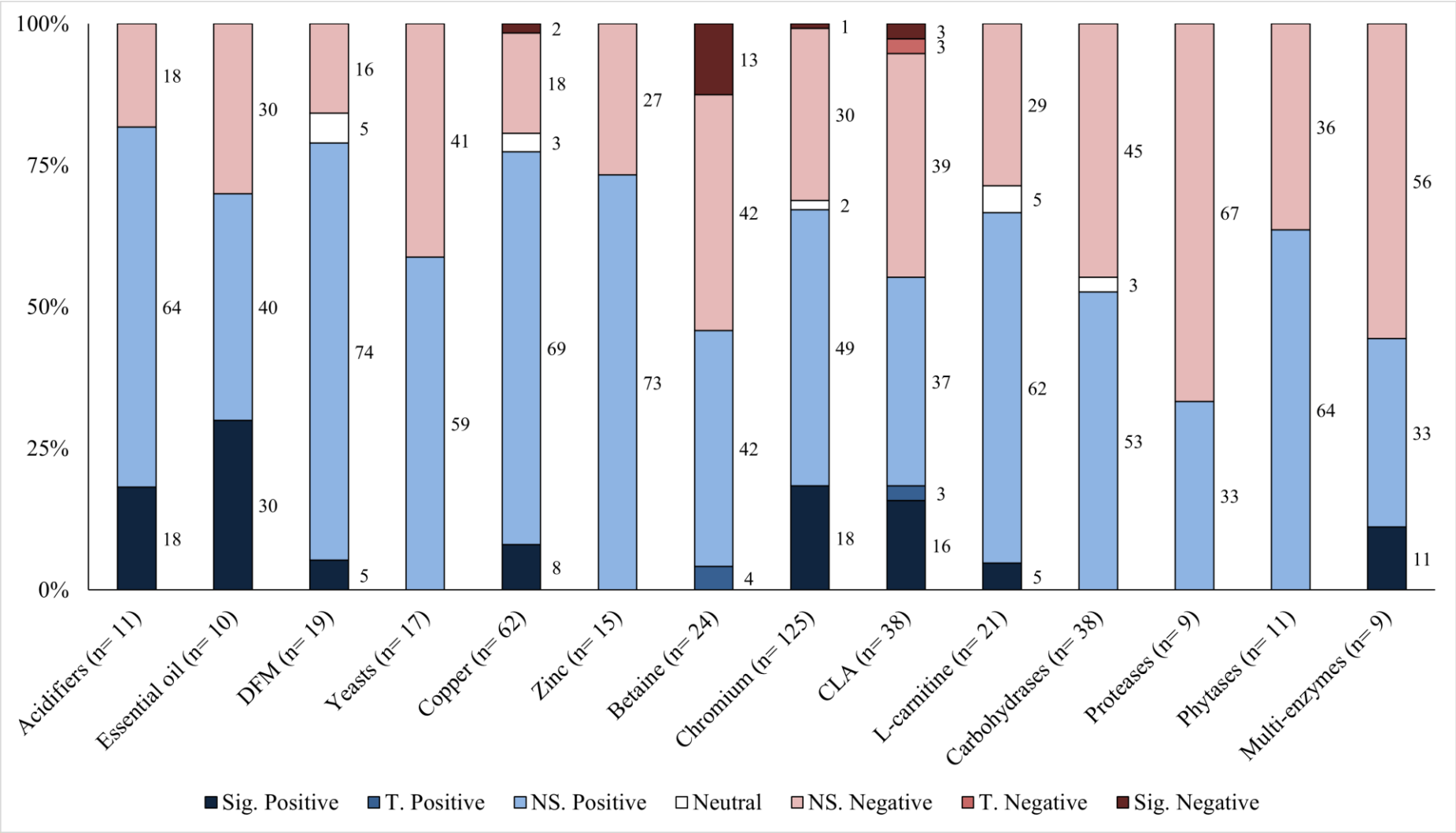

Figure 1.5. The distribution of results for various feed additives on longissimus muscle area/loin depth by significance level and direction.

The comparison was significant (Sig.) if $p \leq 0.05$, had a tendency (T.) if $0.05 < p \leq 0.10$, and was non-significant (NS.) if $p > 0.10$.

Feed Additives—Health

This section discusses the feed additives that can potentially improve growth performance and carcass characteristics by enhancing the health status of grow–finish pigs. The feed additives discussed are acidifiers, essential oils, DFM, yeasts, Cu, and Zn.

Acidifiers—Mechanism of Action

Acidifiers have been used in animal diets for their beneficial effects on antimicrobial activity and nutrient digestibility coefficients. The most used acidifiers are organic acids in the form of short-chain fatty acids (fumaric, citric, malic, formic, lactic, acetic, butyric, and propionic acid), medium-chain fatty acids (sorbic, capric, and caprylic acid), and benzoic acid. Acidifiers lower the pH of the digestive tract, which provides an acidic environment (pH < 4.5) that inhibits the growth of acid-sensitive bacteria [2]. The low pH also assists the digestibility of protein and minerals by stimulating the secretion and activity of enzymes in the small intestine [17,18]. Moreover, in an acidic environment, non-dissociated organic acids can freely penetrate the bacterial cell wall and reduce the pH of cytoplasm [2]. The increased H+ requires bacteria to spend energy on removing these H+ and, therefore, retards the growth of acid-sensitive pathogens [2]. With these mechanisms, acidifiers can potentially improve growth performance and carcass characteristics by enhancing the gut health and digestibility of the pig [2,17,18].

Acidifiers—Results

There were 68 comparisons for ADG between pigs fed a control diet or diets with added acidifiers with an average of a 1.7% increase (range between -14.9 and 11.4%) in pigs fed acidifiers, and for G:F, there were 65 comparisons between pigs fed a control diet or diets with added acidifiers with an average of a 3.1% increase (range between -9.7 and 11.3%) in pigs fed acidifiers. For carcass data, there were 24 comparisons evaluating BF change between pigs fed a

control diet or diets with added acidifiers with an average of a 0.6% decrease (range between -15.3 and 14.4%) in pigs fed acidifiers. For percentage lean, there were 24 comparisons between pigs fed a control diet or diets with added acidifiers with an average of a 0.5% decrease (range between -3.6 and 4.2%) in pigs fed acidifiers. There were 11 comparisons for LMA/LD between pigs fed a control diet or diets with added acidifiers with an average of a 1.6% improvement (range between -7.2 and 8.1%) in pigs fed acidifiers. These results could be expected because the mechanisms do not directly affect protein and lipid metabolism. In summary, feeding acidifiers has the potential to improve growth performance but only minor effects on carcass characteristics.

Essential Oils (EO)- Mechanism of Action

Essential oils (ethereal oils) are classified as phytogenic feed additives. Essential oils are a mixture of volatile and non-volatile compounds extracted from plants (approximately 1% of the wet weight of plants), such as oregano, thyme, rosemary, and garlic [19]. The primary active ingredients in EO are phenols (thymol, carvacrol, eugenol, -cymene). These phenolic components have been widely used for antibacterial, antiviral, antifungal, insecticidal, and antiparasitic activities in humans and animals [5]. For the antibacterial effects, the lipophilic structures of EO can penetrate and disrupt the cell wall and cell membrane of the pathogens, which causes alterations in the cell functions [20], which is similar to the antimicrobial mechanism of the organic acids. The phenolic OH group can also act as an antioxidant by donating hydrogen to free radicals [19]. Moreover, EO may potentially enhance the immune system by interacting with the microbiota of the pigs and altering the lymphocyte population and distribution in the gut [19]. These beneficial mechanisms suggest that EO may potentially improve grow–finish pig growth performance and carcass characteristics.

Essential Oils—Results

For ADG, there were 20 comparisons between pigs fed a control diet or diets with added EO with an average of a 5.8% improvement (range between -2.9 and 18.8%) in pigs fed EO. There were 17 comparisons for G:F between pigs fed a control diet or diets with added EO with an average of a 5.8% improvement (range between -2.6 and 19.9%) in pigs fed EO. Fourteen comparisons evaluated BF between pigs fed a control diet or diets with added EO with an average of a 2.7% decrease (range between -14.2 and 6.3%) in pigs fed EO. For percentage lean, there were 9 comparisons with an average of a 0.9% improvement (range between -2.5 and 2.8%) in pigs fed EO. For LMA/LD, there was an average of a 1.9% improvement (range between -6.3 and 12.3%) in pigs fed EO.

Overall, the results suggest that EO positively affected ADG and G:F. Adding EO alone or in combination with acids has the potential to improve growth performance. However, there was only a small amount of research on EO's effect on growth performance, and only three studies were conducted in the US; therefore, using EO may not be beneficial in US-based conditions. More experiments are needed to determine the effect of including EO in the diets of grow–finish pigs.

Direct-Fed Microbials (DFM) -Mechanism of Action

Direct-fed microbial (DFM) or probiotic products are defined as feed additives that contain live (viable)microorganisms (bacteria and/or yeast) that are beneficial to the host. The most used DFM strains added in grow–finish pig diets are yeast (*Saccharomyces cerevisiae*), and Bacillus and Lactobacillus species either as a single strain or blend based on the articles we collected (the effect of the single addition of yeast in diets was discussed in the yeast section). Adding DFM aims to achieve a healthy and balanced intestinal microbial composition [4]. These

beneficial microorganisms may improve the digestibility of nutrients and reduce the adverse effects of pathogens in the gastrointestinal tract by competitive exclusion, modulation of the immune response, and/or the production of bacteriocins [21]. The inclusion of DFM has been used as an alternative to antibiotics and has shown beneficial effects in research when fed mainly in weaned pig diets.

DFM—Results

There were 71 comparisons for ADG between pigs fed a control diet or diets with added DFM with an average of a 3.3% improvement (range between -6.2 and 20.3%) in pigs fed DFM. For G:F, there were 66 comparisons between pigs with an average of a 3.3% improvement (range between -7.2 and 13.1%) in pigs fed DFM. There was an average 1.5% decrease (range between -18.1 and 20.3%) in BF for pigs fed a DFM vs. a control diet across 21 comparisons. For percentage lean, there were 13 comparisons between pigs fed a control diet or diets with added DFM with an average of a 1.0% improvement (range between -2.0 and 3.6%) in pigs fed DFM. There were 19 comparisons evaluating added DFM for LMA/LD, with an average of a 1.5% improvement (range between -5.8 and 10.9%) in pigs fed DFM.

In summary, DFM can potentially improve the growth performance of grow–finish pigs. However, the small effects and lack of statistical differences of DFM on carcass characteristics may suggest that the mechanisms of DFM do not directly affect pigs' protein and lipid metabolism. It is worth mentioning that there were relatively few US-based studies for DFM; therefore, the effects of DFM in US-based conditions may not be the same as what has been observed to date.

Yeasts—Mechanism of Action

Yeast is a single-cell fungus used in the food industry, ethanol production, and animal feed for its nutritional and health benefits. The most used yeast strain in animal feed is *Saccharomyces cerevisiae*, while *Phaffia rhodozyma* (red yeast) is rarely used. Yeast products are added as live yeast (as a DFM additive), yeast cell wall extracts, or a combination of both. Yeast converts substrates (carbon and nitrogen sources) into carbon dioxide, ethanol, and yeast cell contents through fermentation [6]. The fermented yeast cell culture contains vitamin B, β-glucan, α-mannans polysaccharides, and microbial protein, which can serve as a protein source for animals. The yeast cell wall extracts mainly consist of β-glucan and α-mannan polysaccharides, which have shown prebiotic effects on improving nursery pigs' immune system and gastrointestinal health [6]. Mannan oligosaccharides (MOS) are the side chains of mannan polysaccharides and have been widely studied as an antimicrobial feed additive for their positive effects on microbiota and intestinal morphology in nursery pigs [22]. In addition, MOS reduces the colonization of pathogens by binding to the pathogens and improves gut morphology by increasing the villus height:crypt depth ratio [22].

Yeasts—Results

There were 36 comparisons for ADG between pigs fed diets with added yeasts with an average of a 1.6% improvement (range between -13.7 and 10.3%) in pigs fed yeasts. For G:F, there were 33 comparisons between pigs fed a control diet or diets with added yeasts with an average of a 2.7% improvement (range between -11.7 and 17.7%) in pigs fed diets containing yeasts. There were 21 comparisons evaluating pigs fed diets with added yeasts on BF with an average of a 3.1% decrease (range between -30.7 and 11%) in pigs fed yeasts. For percentage lean, there were 8 comparisons between pigs fed a control diet or diets with added yeasts with an

average of a 1.0% improvement (range between -1.7 and 6.6%) in pigs fed yeasts. Lastly, for LMA/LD, there were 17 comparisons with pigs fed added yeasts having an average of a 1.4% improvement (range between -4.3 and 16.6%).

In summary, yeasts can be a potential feed additive with a relatively large magnitude of improving the growth performance of grow–finish pigs, especially for growth performance.

Copper (Cu)—Mechanism of Action

Copper is an essential trace mineral for several metalloenzymes that play roles in oxidation–reduction reactions, transport of oxygen and electrons, and protection against oxidative stress [3]. Feeding pharmacological levels of Cu has shown growth-promoting effects in weaned and growing pigs by reducing diarrhea frequency and increasing feed efficiency [23,24]. These improvements may be because of Cu's effects on the enzymes (lipase, phospholipase A, lipoprotein lipase) involved in lipid digestion and metabolism [3]. Copper also showed bacteriostatic and bactericidal properties that improve weaned pigs' microbiota, gastrointestinal structure, and immune status [25,26]. However, because Cu accumulates in the liver and other organs when fed above requirement estimates, toxicity should be a concern when provided above 250 mg/kg in pig diets. Feeding excess levels of Cu resulted in hemolysis and organ damage in pigs [3].

Copper—Results

There were 155 comparisons of ADG between pigs fed a control diet or diets with added Cu with an average of a 2.5% improvement (range between -12.2 and 15.2%) in pigs fed pharmacological levels of added Cu. For G:F, there were 149 comparisons between pigs fed a control diet or diets with added Cu with an average of a 1.8% improvement (range between -8.0 and 17.6%) in pigs fed Cu. Seventy-three comparisons evaluated BF between pigs fed diets with

added Cu with an average of a 1.4% decrease (range between -17.0 and 11.5%) in BF of pigs fed Cu. For percentage lean, there were 25 comparisons with pigs fed added Cu having an average improvement of 1.6% (range between -2.7 and 34.7%). For LMA/LD, there were 62 comparisons between pigs fed diets with added Cu with an average of a 2.3% improvement (range between -7.5 and 14.5%).

Most studies used Cu additions of 125 to 250 mg/kg (137 comparisons), and increasing Cu addition did not generally further improve pig performance. The growth-promoting effects of Cu can potentially improve growth performance (2.5 and 1.8% improvement for ADG and G:F); however, with carcass characteristics, the effects were relatively small, with most comparisons finding no evidence of difference.

Zinc (Zn)—Mechanism of Action

Zinc is an essential trace mineral in several important metalloenzymes for the growth and development of animals. High levels (1500 to 4000 mg/kg) of dietary zinc oxide (ZnO) have been widely used as a growth-promotive feed additive in weaned pig diets to improve growth performance and gastrointestinal health [7]. However, the mechanisms of the growth-promotive effect of ZnO are still not fully understood. Zinc oxide may regulate the secretion of ions in the intestine, reduce the inflammatory reaction, stabilize the microbiota, prevent the attachment of pathogens, and improve the gastrointestinal structure [7]. Moreover, for grow–finish pigs, whether high Zn inclusion (above 100 mg/kg) can provide a growth-promotive effect is also unclear.

Zinc—Results

For ADG and G:F, there were 30 comparisons between pigs fed a control diet or diets with added Zn with increases of 0.6% (range between -14.4 and 18.7%) and 1.2% (range between -7.6

and 14.4%), respectively. There were 19 comparisons for BF and pigs fed diets with added Zn had an average of a 0.6% decrease (range between -7.6 and 13.1%). For percentage lean, there were 14 comparisons that observed an average 0.9% improvement (range between -0.4 and 3.9%) in pigs fed Zn. All the comparisons (15) found a 0.2% improvement (range between -2.9 and 2.7%) in LMA/LD.

Overall, the results suggest that Zn had positive but relatively small effects on ADG, G:F, and carcass characteristics. Moreover, there were insufficient data to support whether different types of basal diets and inclusion levels affected the response to added Zn.

Feed Additives—Energy and Lipid Metabolism

This section discusses the feed additives that have the potential to improve growth performance and carcass characteristics by affecting the energy and lipid metabolism of grow–finish pigs. The feed additives discussed are betaine, Cr, CLA, and L-carnitine.

Betaine—Mechanism of Action

Betaine is a trimethyl derivative of glycine that can be widely found in plants and animals. It serves as a methyl group donor along with choline and methionine, and plays a role in synthesizing carnitine, creatine, and methylated AAs. It can also improve the metabolism of methionine by donating a carbon molecule for the remethylation of methionine from homocysteine [8]. In pigs, betaine supplementation increased serum growth hormone (GH) and insulin growth factor 1 (IGF-1), which may improve protein synthesis and growth performance [27,28]. Betaine supplementation may also improve energy utilization, resulting in improved growth performance [29]. For meat quality, betaine is likely to regulate genes responsible for the uptake and oxidation of fatty acids in the muscle, and therefore reduce the body fat percentage of the pigs and change the free fatty acid concentration in muscles. Betaine can also delay the

anaerobic glycolysis after slaughter, affecting muscle pH, pork color, and water-holding capacity [8].

Betaine—Results

There was an average of a 1.3% improvement (range between -8.3 and 27.5%) in ADG across 37 comparisons for pigs fed betaine vs. those fed a control diet. For G:F, there were 35 comparisons and those fed added betaine had on average a 2.7% improvement (range between -6.3 and 23.2%). For BF, there were 32 comparisons between pigs fed a control diet or diets with added betaine with an average of 1.7% in favor of pigs fed betaine (range between -18.6 and 7.4%). For percentage lean and LMA/LD, there were 25 and 24 comparisons, respectively, between pigs fed a control diet or diets with added betaine with an average of a 2.0% (range between -4.8 and 12.4%) and 0.20% (range between -7.0 and 8.9%) improvement in pigs fed betaine.

There were insufficient data to support whether different types of basal diets affected the response to betaine for ADG and G:F. However, betaine may have a more beneficial effect on ADG and G:F in limit-fed pigs [30,31]. In summary, the results suggest that betaine had relatively small positive effects on ADG but may benefit G:F more. Adding dietary betaine to finishing pig diets only significantly affected carcass characteristics in a few experiments.

Chromium (Cr)—Mechanism of Action

Chromium affects several enzymes (adenosine monophosphate-activated protein kinase, tyrosine kinase, etc.) and hormones (IGF-1, triiodothyronine, etc.) that regulate energy metabolism, protein accretion, and fat deposition [9]. The primary mechanism of action for Cr is potentiating the action of insulin by facilitating the binding of insulin to receptors on cell membranes which increases the translocation of glucose transporter type 4 to plasma membrane

and thus improves glucose utilization of these cells [9,32]. For muscle cells, Cr increases glucose and AAs uptake and improves energy metabolism which increases lean accretion and reduces fat deposition [9]. Therefore, Cr has the potential to improve feed efficiency and carcass characteristics of grow–finish pigs.

Chromium—Results

There were 138 comparisons for ADG and G:F between pigs fed a control diet or diets with added Cr with an average of a 1.1% (range between -21.1 and 21.2%) and 1.0% (range between -10.3 and 10.3%) improvement, respectively. In addition, many experiments (133) also evaluated BF change when pigs were fed added Cr with an average of a 3.9% decrease (range between -31.4 and 15%) in BF depth. For percentage lean, there were 105 comparisons with pigs fed added Cr having an average of a 1.6% improvement (range between -7.4 and 14.1%). For LMA/LD, there were 125 comparisons with pigs fed added Cr having an average of a 3.1% (range between -11.6 and 22.6%) improvement.

According to our database, Cr slightly improved ADG and G:F. This is in agreement with a meta-analysis that analyzed data from 31 studies and found that grow–finish pigs fed 200 to 500 µg/kg Cr had improved ($p \leq 0.05$) ADG and G:F compared with the control pigs [33]. Chromium's effect on improving BF, percentage lean, and LMA/LD was relatively large and more consistent than many of the other feed additives reviewed.

Conjugated Linoleic Acid (CLA)—Mechanism of Action

Conjugated linoleic acid is a collective term for fatty acids with 18 carbon-atom structures that are geometric isomers of linoleic acid [34]. These fatty acids contain 2 double bonds on either positions 9 and 11 or 10 and 12 in cis or trans configuration [10]. Conjugated linoleic acids play a significant role in lipid metabolism by inhibiting glucose entry into

adipocytes and increasing the activities of nuclear transcription factors and enzymes that affect fatty acid catabolism; therefore, these effects reduce lipogenesis and potentiate lipolysis through β-oxidation [10]. Thus, CLA can potentially improve growth performance by regulating energy metabolism and improving carcass composition by reducing adipose tissue and increasing lean tissue.

CLA—Results

A 2.1% (range between -14.5 and 14.1%) and 3.5% (range between -7.4 and 16.7%) improvement in ADG and G:F, respectively, were observed in pigs fed added CLA across 57 comparisons. Fifty-nine comparisons with pigs fed added CLA observed an average of a 7.0% decrease (range between -27.5 and 18%) in BF. For percentage lean, there were 37 comparisons with an average of a 2.6% (range between -1.8 and 9.1%) improvement in pigs fed CLA. However, for LMA/LD, there was only an average of a 0.9% increase (range between -7.5 and 11%) with added CLA.

In summary, CLA may improve growth performance, with the greatest chance for improvement being elicited for G:F. In addition, CLA has the potential to reduce BF and increase percentage lean more consistently compared with other feed additives considered in this review.

L-carnitine—Mechanism of Action

L-carnitine is an essential molecule that transports long-chain fatty acids into the mitochondrial matrix, where the fatty acids are oxidized for energy production through β-oxidation [11]. L-carnitine can also promote energy production by regulating important key enzymes for glycolysis and the tricarboxylic acid cycle [11]. However, the concentration of L-carnitine is low in plants (e.g., corn and soybean) typically used in animal feeds [11]. Even

though pigs can produce endogenous L-carnitine, its production is affected by the pig's micronutrient status, and in some situations, endogenous production or renal absorption may not satisfy the requirements [11]. Due to these reasons, the addition of L-carnitine in plant-based swine diets has been investigated in numerous studies for its potential to improve performance and carcass characteristics.

L-carnitine—Results

For ADG and G:F, there were 24 comparisons evaluating pigs fed a control diet or diets with added L-carnitine with an average of a 2.1% (range between -4.8 and 9.4%) and 2.5% (range between -3.6 and 7.7%) increase, respectively, observed in pigs fed L-carnitine. For BF, there were 22 comparisons and an average of a 3.4% decrease (range between -18.2 and 4.8%) in pigs fed L-carnitine. Percentage lean significantly increased ($p \leq 0.05$) by an average of 3.8% (range between -2.6 and 7.6%) for pigs fed added L-carnitine. For LMA/LD, there was an average of a 2.4% improvement (range between -6.4 and 16.2%) in pigs fed L-carnitine (21 comparisons).

Overall, the results suggest that L-carnitine has the potential to improve ADG and G:F (79 and 71% of all the comparisons, respectively) with relatively large improvements. In addition, the results also suggest that L-carnitine is a potential feed additive that had relatively large effects on BF, percentage lean, and LMA/LD compared to other feed additives evaluated in this review.

Feed Additives—Enzymes

This section discusses dietary enzymes used as feed additives in classes of carbohydrases, proteases, phytases, and combination of different types of enzymes (multi-enzymes).

Mechanism of Action—Enzymes

Because endogenous digestive enzymes of pigs cannot fully digest various feed substances (e.g., fiber and phytate), exogenous enzymes are included in diets to improve the digestion of these feed ingredients [12]. Moreover, indigestible fibrous substances can entrap nutrients or negatively affect digestion. Carbohydrases (xylanase, glucanase, mannanase, etc.) can break down some indigestible non-starch polysaccharides (cell wall and fiber) of the plant-based ingredients and release previously unavailable nutrients for the animals [13]. Moreover, the products of this degradation process may be beneficial for gut health [13]. In addition, proteases assist the breakdown of dietary protein to improve utilization and reduce excess protein in the hindgut and manure.

The main reason for adding phytases is to break down dietary phytate and release phytate-bound [35]. Furthermore, phytases may also improve the digestibility of other nutrients (i.e., energy, AAs, minerals, etc.) by reducing the negative effect of dietary phytate on these nutrients [36]. Blending different enzymes into multi-enzyme complexes is common with the intent of combining the benefits because of different enzymatic mechanisms.

Carbohydrases—Results

For ADG, there were 87 comparisons with pigs fed a control diet or diets with added carbohydrases with an average of a 1.3% improvement (range between -9.3 and 14.8%). For G:F, there were 84 comparisons with an average of a 1.7% improvement (range between -12.3 and 16.5%) in pigs fed carbohydrases. There were over 50 comparisons evaluating BF and percentage lean between pigs fed a control diet or diets with added carbohydrases with an average of a 0.4% decrease (range between -17 and 16.1%) or a 0.40% increase (range between -4.8 and 8.1%) in BF and percentage lean, respectively. For LMA/LD, there were 38 comparisons

between pigs fed a control diet or diets with added carbohydrases with an average of a 1.1% improvement (range between -3.5 and 12.7%) in pigs fed carbohydrases. Overall, results suggest that carbohydrases had positive effects on ADG and G:F (63 and 67% of all the comparisons, respectively), but the magnitude was small, and most comparisons had no statistical differences. The mixed and relatively small and non-significant responses are expected because the mechanisms of exogenous enzymes assist the digestion of feed substrates but do not affect protein and lipid metabolism. The high percentage of non-significant comparisons also suggested that the carcass results were highly variable.

Proteases—Results

There were 23 comparisons for ADG between pigs fed a control diet or diets with added proteases with an average of a 0.6% improvement (range between -9.8 and 6.0%) in pigs fed proteases. For G:F, there were 22 comparisons with an average of a 1.8% improvement (range between -4.3 and 15.1%) in pigs fed proteases. Comparisons between pigs fed a control diet or diets with added proteases showed an average of a 0.1% decrease (range between -8.3 and 10.8%) in BF of pigs fed proteases. There was no difference (range between -2.1 and 2.4%) in percentage lean across 13 comparisons between pigs fed a control diet or diets with added proteases. For LMA/LD, there were 9 comparisons between pigs fed a control diet or diets with added proteases with an average of a 2.0% decrease (range between -6.5 and 5.4%) in pigs fed proteases.

Overall, there were relatively small and non-significant results observed in growth performance and carcass characteristics when proteases were included in grow–finish pig diets.

Phytases—Results

An average of a 1.1% improvement (range between -4.6 and 10.6%) in ADG of pigs fed phytases was observed across 24 comparisons between pigs fed a control diet or diets with added phytases. Feed efficiency was improved by 1.1% (range between -6.6 and 6.9%) across 24 comparisons between pigs fed a control diet or diets with added phytase. There were 14 comparisons for BF between pigs fed a control diet or diets with added phytases with an average of a 0.2% decrease (range between -6.7 and 8.3%) in pigs fed phytases. No differences (range between -0.8 and 1.3%) were observed in percentage lean with 9 comparisons between pigs fed a control diet or diets with added phytases. For LMA/LD, there were 11 comparisons between pigs fed a control diet or diets with added phytases with an average of a 1.4% decrease (range between -11.6 and 3.5%) in pigs fed phytases.

In summary, including phytase in diets with adequate P may not affect finishing pig ADG and G:F. Furthermore, there were relatively small and non-significant results observed in carcass characteristics when phytases were included in grow–finish pig diets.

Multi-Enzymes—Results

For ADG, there were 29 comparisons between pigs fed a control diet or diets with added multi-enzymes with an average of a 3.1% improvement (range between -6.5 and 24.9%) by the addition of multi-enzymes. A 3.3% improvement (range between -6.6 and 30.8%) in G:F of pigs fed multi-enzymes was observed across 29 comparisons. There were 12 comparisons for BF between pigs fed a control diet or diets with added multi-enzymes with an average of a 2.8% increase (range between -12.3 and 29.4%) in pigs fed multienzymes. There were 9 comparisons in percentage lean and LMA/LD between pigs fed a control diet or diets with added multi-enzymes with an average of a 0.7% (range between -1.3 and 4.4%) and 0.30% (range between -

3.2 and 11.3%) improvement in pigs fed multi-enzymes. Overall, results suggest that multi-enzymes positively affect ADG and G:F. There were relatively small and non-significant results observed in carcass characteristics when multi-enzymes are included in grow–finish pig diets. Moreover, the combination of multiple enzymes provided greater improvement than adding any single type of enzyme (carbohydrase, protease, and phytase) alone according to our summaries, which suggests that different types of enzymes may have a synergetic effect; however, some factorial studies that used multi enzyme types found combining enzyme types do not improve performance [37,38].

Furthermore, most comparisons showed little or negative effects in US-based research; therefore, US-based diets with multi-enzymes should be evaluated further.

Discussion

Overall, the greatest proportion of the comparisons for each feed additive was positive; however, most of them were also not statistically significant (Tables 1.1–1.5). For most feed additives, there were enough comparisons to show the general effects on ADG and G:F. For carcass characteristics, the overall effects were also positive; however, there were fewer comparisons, and effects were mostly small and inconsistent (Figures 1.1–1.5). Moreover, the sampling process for carcass characteristics often only selects a smaller portion of the animals that were used for the growth performance data, which accentuated the between-animal variations for the relatively small treatment effects. This potentially resulted in a higher proportion of the comparisons having no evidence of difference for carcass characteristics.

For utilizing these results in US-based production, the results suggest that Cr, carbohydrases, proteases, phytases, and Zn had minor effects and did not appear to be potential feed additives based on growth performance. Essential oils consistently improved ADG and G:F

with a relatively larger magnitude (>3%), but the number of comparisons was low, and most studies were not US-based; therefore, publication bias and locational effect should be concerned. On the other hand, acidifiers, betaine, CLA, L-carnitine, and yeasts had relatively substantial positive effects (2.5 to 3.5 %) on G:F. Moreover, despite limited data, benzoic acid and other acidifiers may be potential additives for improving ADG and G:F, but further research is needed. The effects of Cu were most studied, with a 2.5% improvement in ADG, but the average effect on G:F was minor (1.8%). Moreover, DFM and multi-enzymes had relatively large and consistent improvements (approximately 3%) in ADG and G:F with a sizeable number of comparisons; however, there were relatively few US-based studies for DFM. Therefore, acidifiers, betaine, CLA, DFM, multi-enzymes, L-carnitine, and yeasts may have the greatest opportunity to improve finishing pig G:F. However, their concentration and feeding strategies need further research. Lastly, betaine, Cr, CLA, and L-carnitine may potentially improve carcass characteristics because of their effects on lipid and energy metabolism.

Additionally, even though we collected all the known research studies, publication bias still needs to be kept in mind when interpreting the results of this literature review. Furthermore, most research was conducted in well-controlled research facilities that only utilized a small number of pigs per experiment; therefore, it may have limitations in representing the whole pig population. Moreover, compared with pigs in commercial settings, these research pigs were observed closely, experienced relatively little environmental stress (e.g., space allowance and temperature), and often had better health status and high feed intake (nutrient intake) relative to the pigs' requirements. Therefore, adding these feed additives may be more advantageous in pigs' diets in commercial settings where pigs are not under optimal conditions. More commercial research should be conducted to understand the effects of additives used under these conditions.

Additionally, to utilize these results, the location of these studies should also be considered because some additives (e.g., DFM and EOs) had large positive responses in some countries, but, in contrast, the US-based results showed neutral or negative responses. These may be due to the differences in pig genetics, farm environments, formulated nutrient levels, and diet compositions. Lastly, even though economics was not discussed in this review, the decision to include feed additives in pig diets should consider the return of investment based on the price and the magnitude of benefit of the feed additive. For example, a relatively small magnitude of G:F improvement may still be economical when provided by a relatively low-priced feed additive. On the other hand, a feed additive with a relatively large magnitude of improvement in G:F may not be economical if it has a relatively high price.

Conclusions

In conclusion, this literature review collected available research on finishing pig feed additives to provide a descriptive analysis of the effects on growth and carcass performance. In addition, this database has the potential to be further analyzed with advanced statistical methods, such as meta-analysis, to figure out the reasons behind the variable results when additives were added, and possibly lead to a better understanding of the effect of feed additives to improve the efficiency of swine production.

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Chapter 2 - Evaluation of selenium source on nursery pig growth performance, serum and tissue selenium concentrations, and serum antioxidant status.

Abstract

A total of 3,888 pigs (337 × 1050, PIC, Hendersonville, TN; initially 6.0 ± 0.23 kg) were used in a 35-d study. At the time of placement, pens of pigs were weighed and allotted to 1 of 3 dietary treatments in a randomized complete block design with blocking structure including sow farm origin, date of entry into the facility, and average pen BW. A total of 144 pens were used with 72 double-sided 5-hole stainless steel fence line feeders, with one feeder serving as the experimental unit. For each feeder, 1 pen contained 27 gilts, and 1 pen contained 27 barrows. There were 24 replicates per dietary treatment. Diets were fed in three phases, and all contained 0.3 mg/kg added Se. A common phase 1 diet contained added Se from sodium selenite and was fed in pelleted form to all pigs from d -7 to approximately d 0. Three Se sources [sodium selenite; Se yeast; or hydroxy-selenomethionine (**OH-SeMet**;] were used to formulate 3 experimental diets in meal form for phase 2 (d 0 to 14) and phase 3 (d 14 to 35). During the pre-treatment period(d -7 to 0), there was marginally significant evidence ($P = 0.097$) of a difference in ADFI between treatments, although no significant pairwise differences were observed ($P > 0.05$). There were no other differences in growth performance between treatments from d -7 to 0. Clinical disease attributed to *Streptococcus suis* was observed within the trial between d 0 and 14, and water-soluble antimicrobial therapy was administered to all treatment groups for 7 d. From d 0 to 35, pigs fed OH-SeMet tended to have decreased ADG ($P < 0.10$) and had increased ($P < 0.05$) serum and tissue selenium concentration compared to other treatments. There was

marginally significant evidence of a source × day interaction for total antioxidant capacity (**T-AOC**) where the numerical increase over time was less for the OH-SeMet than sodium selenite or selenium yeast treatments. There was no difference ($P > 0.05$) in antioxidant status as measured by serum GSH-Px or TBARS assay between treatments. In summary, compared to sodium selenite and selenium yeast, OH-SeMet had greater bioavailability as indicated by increased serum and tissue selenium concentration; however, antioxidant status was similar between treatments and OH-SeMet tended to reduce growth performance compared with pigs fed sodium selenite.

Introduction

Selenium (Se) is an essential trace mineral for selenoproteins that are crucial for all stages of animal production because of their roles as antioxidant enzymes [e.g., glutathione peroxidase (GSH-Px) and thioredoxin reductase] that protect cells from oxidative damage (NRC, 2012; Hosnedlova et al., 2017). Selenium deficiency may result in sudden death, pale muscle, liver necrosis, mulberry heart disease, and damage to lungs and gastrointestinal tissues in pigs (NRC, 2012; Hosnedlova et al., 2017). Therefore, meeting the dietary Se requirement is important for animal production, especially in regions that use feed ingredients grown in low Se soils (Hosnedlova et al., 2017). For swine production, the dietary Se requirement ranges from 0.3 mg/kg for nursery pigs to 0.15 mg/kg for growing-finishing pigs and sows (NRC, 2012). Even though Se is an essential trace mineral for pigs, there is a narrow range between requirement and toxicity (Shini et al., 2015). Excess Se excretion in animal waste can cause environmental pollution (NRC, 2012). Thus, the Food and Drug Administration (FDA) regulates the addition of Se in swine diets, and the maximum level of added dietary Se is 0.3 mg/kg in complete feed for all stages of production (FDA, 2021). To meet this requirement, several inorganic or organic Se

sources can be added to animal feed. Sodium selenite is commonly used as the primary inorganic Se source. In nature, organic Se is predominantly found in seleno-amino acid forms where Se replaces the S in sulphur-containing AAs, such as cysteine and methionine, to form selenocysteine and selenomethionine (Shini et al., 2015). Commercial organic Se sources used in animal feed are in the form of selenomethionine, such as Se yeast or hydroxy-selenomethionine (OH-SeMet). Different Se sources have shown bioavailability differences in animals due to the structural differences that affect absorption and storage of Se and may improve an animal's performance (Shini et al., 2015). Nursery pigs fed 0.3 mg/kg OH-SeMet had increased tissue Se levels compared to pigs fed sodium selenite without a difference in growth performance (Chao et al., 2019). Growing pigs fed organic Se sources (Se yeast or OH-SeMet) had greater ($P < 0.05$) plasma and muscle Se concentrations compared to pigs fed inorganic Se source (sodium selenite) without differences ($P > 0.05$) in growth performance (Jlali et al., 2014). However, the differences between these products added to diets formulated with corn and soybean meal originating from low soil Se regions and fed to nursery pigs are still not clear. Therefore, the objective of this study was to determine the effect of Se source (sodium selenite, Se yeast, and OH-SeMet) included at the legal limit in the United States of 0.3 mg/kg added Se on growth performance, serum and tissue Se concentrations, and serum antioxidant status of nursery pigs.

Material and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this study. Experiments were conducted at a commercial research facility in north-central Ohio (Bucyrus, OH). Weaned pigs (approximately 21 d of age) from three sow farms entered the research facility over a 7-d period. Sows were fed diets containing 0.3 mg/kg of added Se with a minimum of 50% from yeast-derived organic Se and the remainder from

sodium selenite. At the time of weaning (d -7), a total of 3,888 pigs (337 × 1050, PIC, Hendersonville, TN; initially 6.0 ± 0.23 kg) were placed in the research barn with 27 pigs per pen (2.2 × 2.7 m). A total of 144 pens were used with 72 double-sided 5-hole stainless steel fence line feeders, each feeding 2 adjacent pens with feeder serving as the experimental unit. For each feeder, 1 pen contained 27 gilts, and 1 pen contained 27 barrows. Each pen also contained a cup-waterer to provide *ad libitum* access to feed and water. At the time of placement in the nursery facility, pens of pigs were weighed and allotted to 1 of 3 dietary treatments in a randomized complete block design with blocking structure including sow farm origin, date of entry into the facility, and average pen bodyweight. There were 24 replicates (feeders) per dietary treatment.

There was an increase in clinical disease associated with *Streptococcus suis* above expected levels in the research barn during the phase 2 period (d 0 to 14) for approximately a week. Amoxicillin (250 mg/5mL; NDC 0781-6041-55; Sandoz, Princeton, NJ) was administered through the water to all pens for 7 d.

Diets

Samples of corn, soybean meal, and enzymatically-treated soybean meal (HP300, Hamlet Protein Inc., Findlay, OH) were collected and analyzed for Se concentration at the Michigan State University Veterinary Diagnostic Laboratory (**MSU VDL**, East Lansing, MI) prior to initiation of the study. The trace mineral premix used in the treatment diets did not contain Se (SEM Minerals, L.P., Quincy, IL). Diets were fed in three phases, and all contained 0.3 mg/kg added Se (Table 2.1). Phase 1 common diet was formulated with added Se from sodium selenite, manufactured and pelleted at Premier Feeds, LLC (Urbana, OH), and was fed to all pigs from weaning to approximately 6.0 kg BW with a feed budget of 0.68 kg/pig. Three Se sources (sodium selenite, Se yeast, and OH-SeMet) were used to formulate 3 experimental diets for

phase 2 and 3, and were manufactured at the Hord Elevator (Bucyrus, OH). Phase 2 and 3 diets were fed in meal form with a feed budget of 11.6 and 14.5 kg/pig, respectively. The phase 1, 2, and 3 diets were fed approximately from d -7 to 0, d 0 to 14, and d 14 to 35, respectively. All diets met the NRC (2012) vitamin and mineral requirement estimates.

Feed samples were collected from at least 6 feeders per treatment per phase, pooled, and subsampled for Se concentration (MSU VDL) and crude protein (Kansas State University Swine Laboratory, Manhattan, KS; Table 2.2). The feed Se assay was based on an Agilent Technologies Inc. (Santa Clara, CA) method using an inductively coupled plasma mass spectrometer (**ICP/MS**). The ICP/MS was tuned to yield a minimum of 7500 cps sensitivity for 1ppb yttrium (mass 89), less than 1.0% oxide level as determined by the 156/140 mass ratio and less than 2.0% double charged ions as determined by the 70/140 mass ratio. Selenium concentration was calibrated using a 6-point linear curve of the analyte-internal standard response ratio. Standards were from Inorganic Ventures (Christiansburg, VA). A National Institute of Standards and Technology (**NIST**; Gaithersburg, MD) typical diet standard was used as a control.

Data and sample collection

Feed additions to each feeder were made and recorded by an electronic feeding system (Dry Exact; Big Dutchman, Inc. Holland, MI). Pens of pigs were weighed by pen, and feed disappearance was calculated every 7 d until the study's conclusion to calculate ADG, ADFI, average BW, and G:F. Feed disappearance was measured using a volumetric regression equation which estimates the quantity of feed remaining in the feeder subtracted from the quantity of feed added to the feeder.

Serum samples were collected from 1 median weight barrow of each experimental unit on d 0, 14, and 35 of the experiment. The same pig per experimental unit was marked with high visibility, numbered ear tag on d 0, and used in all subsequent serum collections. Serum samples

from two pigs could not be collected due to the removal of the pig from the study; therefore, replacement barrows from the same pen were randomly selected and used for further sampling. Whole blood samples were allowed to clot for 30 min, centrifuged at 1,500 × g for 15 min., and the resulting serum supernatants were divided into 7 polypropylene tubes as aliquots and transferred and stored at -80°C. Day 0 serum samples were collected when all pigs were still on the phase 1 common diet formulated with sodium selenite. Serum Se concentration was analyzed on d 0, 14, and 35 samples at the MSU VDL. The serum Se assay used a similar method as the feed Se analysis but with in-house serum pools as the controls. Serum glutathione peroxidase (GSH-Px), total antioxidant capacity (T-AOC), and thiobarbituric acid reactive substances (TBARS) were evaluated on d 14 and 35 samples at the Kansas State University Swine Laboratory (Manhattan, KS). For serum GSH-Px, assay kits were purchased from Cayman Chemical Company (Ann Arbor, MI; # 703102). For serum T-AOC, assay kits were purchased from Cell Biolabs, Inc. (OxiSelec, San Diego, CA; # STA-360). For TBARS, the assay was a modification of the methods of Yagi (1998) and Aguilar Diaz De Leon and Borges (2020). Serum GSH-Px, T-AOC, and TBAR samples were run in triplicate in 96-well microplates with an intra-assay CV of ≤ 5.0%. The malondialdehyde bis (MDA bis) standard curve was prepared freshly for each 96 well microtiter plate with a range of 1.56 to 100 μM MDA. A total of 100 μL of each standard or undiluted serum sample was added to each test tube, and then 200 μL of 10% TCA solution was added for MDA extraction. The solution was mixed with 1.0 mL of TBA/sodium acetate and incubated in a boiling water bath (95 °C) for 60 min. After incubation, test tubes were placed in an ice bath for 15 min and then centrifuged at 1500 × g for 10 min at 4 °C. Immediately after centrifugation, 150 μL of supernatant was aliquoted from each tube and placed into a separate well of a 96 well microtiter plate. The absorbance was read at 532 nm with

a spectrophotometer. The average absorbance reading of the blank samples was subtracted from all other absorbance readings. A standard curve was created by plotting the blank-subtracted absorbance readings and the known concentrations of each standard. Sample data points were then fitted using the equation of the linear regression line obtained from the standard curve to calculate sample concentrations.

The same 72 barrows used for serum collection were euthanized with a penetrative captive bolt pistol on d 35 of the experiment for the collection of muscle and liver tissue by a licensed veterinarian for consistency of sample collection. Muscle samples were collected from the loin at the 10^{th} rib. Liver samples were collected from the right median lobe adjacent to the gallbladder. Following collection, fresh tissue samples were stored on ice and transported to the MSU VDL for analysis of tissue Se concentration. The tissue Se analysis used a similar method as the feed Se analysis, but with NIST bovine liver and muscle standards as controls.

Statistical analysis

Data were analyzed as a randomized complete block design for one-way ANOVA using the lmer function from the lme4 package for growth performance, percentage of injectable treatments, Se concentration, and antioxidant status, and the glmer function (binomial distribution) from the lme4 package for the percentage of removal and mortality in R program (R core team, 2019; Vienna, Austria). Feeder (2 pens of pigs) was considered the experimental unit. Initial pen average BW, sow farm origin, and date of entry into the facility were the blocking factors. Treatment was used as the fixed effect. For d 0 to 35 growth performance, d -7 to 0 ADFI was used as a covariate because of the tendency of difference between treatments. For serum selenium concentration, d 0 selenium concentration was used as a covariate for d 14 and 35 serum selenium concentrations which were analyzed as repeated measures. For the serum GSH-Px, T-AOC, and TBARS assay, a microtiter plate was used as a random effect, and serum

samples were balanced for the block when placed on microplates. For the serum GSH-Px assay, T-AOC, and TBARS were analyzed in triplicate, duplicate, and triplicate, respectively. Data were analyzed by accounting for subsampling and repeated measures over time. Tukey adjustment was used for multiple comparisons. All results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results

Growth performance

From d -7 to 0 (pre-treatment period), there was no evidence of difference ($P > 0.05$) in d -7 BW, d 0 BW, ADG, and G:F between treatment groups (Table 2.3). However, despite the common diet, there was marginally significant evidence of a difference ($P = 0.097$) in ADFI between treatments from d -7 to 0, with the OH-SeMet having a numerically lower ADFI compared to the other treatment groups; therefore, d -7 to 0 ADFI was used as a covariate for growth performance in subsequent periods and overall growth performance. From d 0 to 14, pigs fed OH-SeMet had decreased ($P < 0.05$) ADFI and consequently lower ADG compared to pigs fed the other two treatments. There was no evidence of difference ($P > 0.05$) in G:F between treatments. From d 14 to 35, there was no evidence of difference ($P > 0.05$) in any growth criteria between the three treatments. From d 0 to 35, pigs fed OH-SeMet tended to have decreased ADG ($P < 0.10$) compared to pigs fed sodium selenite. From d -7 to 35 (overall period), pigs fed OH-SeMet tended to have decreased ADFI ($P < 0.10$) compared to pigs fed sodium selenite. However, for the same period, there was no evidence of difference ($P > 0.05$) in ADG, G:F, d 35 BW, percentage of injections, removal, and mortality between treatments.

Serum and tissue Se concentration

There was a tendency ($P = 0.072$) of source × day interaction for serum Se (Table 2.4). Pigs fed OH-SeMet had a greater increase in serum Se from d 14 to 35 than pigs fed sodium selenite or selenium yeast. On d 14, pigs fed OH-SeMet had increased ($P < 0.05$) serum selenium concentration compared to pigs fed selenium yeast. On d 35, despite a lower ADFI, pigs fed OH-SeMet had increased ($P < 0.05$) serum, muscle, and liver selenium concentration compared to all other treatments.

Antioxidant status

There was a marginally significant increase in GSH-Px ($P = 0.074$) over time; however, no source × day interaction or main effect of the source was observed ($P > 0.10$; Table 2.4). A source × day interaction ($P = 0.027$) was found on serum T-AOC. Although no significant means separation was present, pigs fed OH-SeMet had a smaller numerical increase in serum T-AOC from d 14 to 35 compared to pigs fed sodium selenite or selenium yeast. Additionally, there was a marginally significant increase in T-AOC over time ($P = 0.089$). There was no evidence of a source × day, source, or day effect for TBARS ($P > 0.10$).

Discussion

Effects of Se sources on growth performance

Consistent with a limited number of previous trials with nursery and growing pigs, different Se sources did not affect growth performance. Chao et al. (2019) found no evidence of difference ($P > 0.05$) in growth performance between nursery pigs fed 0.3 mg/kg added Se from sodium selenite and OH-SeMet. Cao et al. (2014) reported no evidence of difference ($P > 0.05$) in growth performance between nursery pigs fed different levels of DL-SeMet (0.1 to 0.7 mg/kg) or between pigs fed 0.3 mg/kg Se from DL-SeMet and sodium selenite. Jlali et al. (2014) also

reported no evidence of difference ($P > 0.05$) in growth performance between growing pigs fed either 0.1 or 0.3 mg/kg added Se from sodium selenite, Se yeast, or OH-SeMet. Moreover, Mahan et al. (1999) found no evidence of difference ($P > 0.05$) in growth performance between growing-finishing pigs fed 0.3 mg/kg of sodium selenite or Se yeast. However, the present study observed a reduction in early phase ADFI in nursery pigs fed OH-SeMet compared to pigs fed sodium selenite or Se yeast. The feed, serum, and tissue Se concentration analysis confirmed that OH-SeMet was added to the diets; therefore, we concluded that the reduction in ADFI was not caused by Se deficiency. In addition, factors that might reduce ADFI were closely examined, and no bias was found.

Effects of Se sources on serum and tissue Se concentration

For normal pigs, Ullrey (1987) and Mahan (1991) suggested that the serum Se concentration ranges from 0.08 to 0.15 ppm, while Blood and Radostits (1989) considered above 0.120 μg/ml serum as normal levels. These suggest that all pigs from the three Se sources had serum Se concentration within normal range without deficiency. The inorganic and organic forms of Se are both used as feed mineral additives along with Se provided from other feed ingredients to meet the Se requirement of pigs; however, organic Se sources have been shown to have greater bioavailability than inorganic sources (Shini et al., 2015). Other studies comparing pigs fed OH-SeMet to sodium selenite observed similar results as our study. Chao et al. (2019) reported increased serum, liver, kidney, and muscle Se concentration in nursery pigs fed OH-SeMet compared to sodium selenite. Mahan et al. (1999) and found that growing-finishing pigs fed Se yeast had greater (Se source × Se level, $P < 0.01$) increases in tissue Se as dietary Se level increased from 0.05 to 0.3 mg/kg compared to sodium selenite. Similarly, Mahan et al. (2014)

also found that growing-finishing pigs fed Se yeast had greater serum Se and tissue Se (loin, liver, and heart) compared to sodium selenite. Growing pigs fed 0.3 mg/kg of added Se from OH-SeMet had the highest ($P < 0.05$) plasma, liver, and muscle Se concentration, followed by Se from Se yeast, and sodium selenite had the lowest concentration (Jlali et al., 2014). A similar result was reported in another study where growing pigs fed L-SeMet had the highest ($P < 0.05$) tissue Se concentration, followed by Se yeast and then sodium selenite (Falk et al., 2018). In a meta-analysis, Zhou et al. (2021) observed that sows fed organic Se sources had 29% greater serum Se concentration than inorganic Se sources. However, we observed no evidence of difference in pigs fed Se yeast compared to sodium selenite. Cao et al. (2014) also found no evidence of difference in plasma Se concentration between nursery pigs fed 0.3 mg/kg of Se from sodium selenite and DL-SeMet. By comparing the results herein with these previous studies, we can conclude that OH-SeMet has the greater bioavailability, followed by Se yeast, and sodium selenite. To understand the differences in bioavailability between Se sources, differences in Se absorption across the intestine wall should be considered. Inorganic Se, such as sodium selenite, is absorbed passively across the intestinal wall as ions, while selenomethionine is absorbed actively with AA or peptide transporters on the enterocytes (Mahima et al., 2012; Shini et al., 2015).

Moreover, the chemical properties of inorganic Se ions may form insoluble complexes with other feed components or interact with phytate in the digesta, which reduces the absorption of Se across the intestine wall (Mahima et al., 2012). On the other hand, organic Se, as a result of Se being bound to AAs, forms stable complexes that are less prone to interact with other feed components (Mahima et al., 2012). After absorption, both inorganic and organic Se are converted to selenocysteine or selenoproteins in the enterocytes and then transported via the

portal vein to the liver, where selenocysteine is converted into selenoprotein P or extracellular GSH-Px for peripheral tissue, such as kidney and muscle (Shini et al., 2015). Consequentially, these factors result in the greater absorption/bioavailability of organic Se sources, as observed in the increased serum and tissue Se concentrations.

Effects of Se sources on antioxidant status and health

Because organic Se source elevates the Se status of animals, we were interested in whether this increase can translate to an elevated antioxidant status. The results of our study and the previous studies showed that the effects of Se sources on antioxidant status have some inconsistencies, which might be caused by the differences in the concentrations of Se in the basal diets, the oxidative stress caused by the environment, and/or the stage of production. We found no evidence of difference between sources of Se in the antioxidant status of nursery pigs. Mahan et al. (1999) and Mahan et al. (2014) observed no evidence of difference ($P > 0.05$) in serum GSH-Px between growing-finishing pigs fed 0.3 mg/kg of sodium selenite or Se yeast. Cao et al. (2014) reported no evidence of difference ($P > 0.05$) in serum MDA, liver GSH-Px, liver T-AOC, liver MDA, muscle T-AOC, and muscle MDA between nursery pigs fed 0.3 mg/kg added Se from sodium selenite and DL-SeMet; however, pigs fed DL-SeMet had increased ($P < 0.05$) serum GSH-Px, serum T-AOC, muscle GSH-Px compared to sodium selenite. Chao et al. (2019) found no evidence of difference ($P > 0.05$) in serum T-AOC, serum GSH-Px, liver GSH-Px, and liver MDA between nursery pigs fed 0.3 mg/kg added Se from sodium selenite and OH-SeMet; however, pigs fed OH-SeMet had reduced ($P < 0.05$) serum MDA and increased ($P < 0.05$) liver T-AOC compared to sodium selenite. These experiments suggest that there were some differences in antioxidant status between feeding 0.3 mg/kg of inorganic and organic Se sources

for pigs in their growing stage, but the growth performance result showed no difference. However, these experiments were conducted in research facilities that may have lower oxidative stress from the environment and pathogens compared to commercial facilities. Therefore, the increased Se status did not consistently benefit the antioxidant system in these experiments. Moreover, pigs have lower feed intake in commercial facilities compared to research facilities; thus, the magnitude of the bioavailability of Se sources may play a more important role in commercial facilities. In a meta-analysis, the authors observed that sows fed organic Se sources had 6.4% higher GSH-Px activity than inorganic Se sources (Zhou et al., 2021). This consistent improvement may be because sows are under constant oxidative stress during gestation and lactation; therefore, the increase in tissue Se level from organic Se may benefit the antioxidant status and performance of the animals (Zhou et al., 2021).

Selenium supplementation with OH-SeMet during the gestation period improved ($P < 0.05$) litter weight gain, antioxidant status, and intestinal antioxidant capacity, and reduced ($P < 0.05$) birth interval and inflammation level compared to sodium selenite (Mou et al., 2020a; Mou et al., 2020b; Mou et al., 2021). By implication, organic Se may also be beneficial in growing pigs under greater environmental or pathogenic oxidative stress. Even though the Se was not directly fed to the piglets, LPS-challenged weaned pigs from sows fed OH-SeMet had improved antioxidant status and reduced inflammation levels compared to piglets from sows fed sodium selenite (Mou et al., 2020a; Mou et al., 2021). Doan et al. (2020) challenged nursery pigs with diquat and found no evidence of difference ($P > 0.05$) in post-challenge ADFI and BW between challenged pigs fed Se yeast and pigs without challenge. However, they observed improved ($P < 0.05$) antioxidant status in challenged pigs fed Se yeast compared to challenged nursery pigs fed sodium selenite. On the contrary, even though our pigs were reared under commercial

conditions, we observed no difference in antioxidant status between Se sources when pigs experienced Streptococcus suis challenge. However, the challenge was not planned or controlled, and pigs may have recovered from the pathogen challenge before the blood samples were taken on d 14 of the trial. Therefore, more research is needed to confirm the effect of organic Se sources in pigs under oxidative stress or challenges.

In conclusion, organic Se sources, especially OH-SeMet, provided greater Se bioavailability as indicated by the increased serum and tissue Se concentration. However, the improved Se reservoir did not affect the pigs' growth performance, health status, or antioxidant status. This indicates that under the conditions of this experiment, both inorganic and organic Se sources added at 0.3 mg/kg can provide adequate Se to meet the pigs' requirement. A higher Se reservoir in tissue may benefit health and antioxidant status when pigs are under high oxidative stress. However, more studies are needed to confirm the effect of the organic Se source used in these scenarios.

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Table 2.1. Diet composition, (as-fed basis)[1]

Item	Phase 1	Phase 2	Phase 3
Ingredients, %			
Corn	35.00	60.64	62.90
Soybean meal	21.90	30.27	31.34
Dried whey	25.00	--	--
Soft red wheat	5.00	--	--
Enzymatically treated soybean meal[2]	5.00	2.50	--
Corn oil	3.50	1.50	1.50
Limestone, ground	0.83	1.10	1.05
Monocalcium phosphate	0.90	1.10	0.95
Salt	0.35	0.50	0.35
L-Lys HCl	0.50	0.50	0.45
DL-Met	0.33	0.28	0.21
Thr source[3]	0.26	0.33	0.28
L-Trp	0.08	0.06	0.05
L-Val	0.21	0.15	0.10
Phytase[4]	0.05	0.10	0.10
Choline chloride	0.04	--	--
Vitamin premix[5]	0.05	0.05	0.05
Sodium metabisulfite	0.50	0.50	0.50
Zinc oxide	0.38	0.26	--
Copper sulfate	--	0.03	0.03
Trace mineral premix[6]	0.10	0.10	0.10
Se source[7]	0.05	0.05	0.05
Total	100.00	100.00	100.00
Standardized ileal digestible (SID) amino acids, %			
Lys	1.42	1.38	1.30
Iso:Lys	55	56	57
Leu:Lys	105	113	117
Met:Lys	42	40	38
Met and Cys:Lys	62	61	59
Thr:Lys	66	65	65
Trp:Lys	21.8	20.7	20.2
Val:Lys	72	71	69
His:Lys	32	36	37
Net energy, kcal/kg	2,628	2,469	2,467
Crude protein, %	20.6	21.9	21.0
Ca, %	0.74	0.75	0.70
STTD P,[8] %	0.59	0.50	0.47

[1]Corn, soybean meal, HP300 (Hamlet Protein Inc., Findlay, OH), sodium selenite, Se yeast, and OH-SeMet (hydroxy-selenomethionine) were analyzed for Se concentration prior to the study at Michigan State University Veterinary Diagnostic Laboratory (East Lansing, MI). Analyzed Se concentration: Corn (0.06 mg/kg), soybean meal (0.275 mg/kg), HP300 (0.321 mg/kg), sodium selenite (640.1 mg/kg), Se yeast (648.8 mg/kg), and OH-SeMet (657.8 mg/kg). Basal Se concentration was calculated based on ingredient sample analysis prior to the study for corn, soybean meal, and HP300 at the MSU VDL, and Se concentration for dried whey and wheat were from NRC (2012). The basal Se concertation for phase 1, 2, and 3 were 0.141, 0.128, and 0.124 mg/kg respectively. All diets had 0.3 mg/kg added Se from either Se sources.

[2]HP300 (Hamlet Protein Inc., Findlay, OH) is an enzyme-treated soybean meal.

[3]L-Threonine was used in phase 1 diet, and Thr pro Biomass (CJ Bio America, Fort Dodge, IA) was used in phase 2 and 3 diets.

[4]Quantum Blue 5G (AB Vista, Plantation, FL) was used in phase 1 diet and provided 2,002 FTU per kg of diet with an expected STTD P release of 0.13%. Quantum Blue 2G was used in phase 2 and 3 diet, and provided 2,002 FTU per kg of diet with an expected STTD P release of 0.14%.

[5]Vitamin premix provided per kg of diet: 5,512 IU vitamin A; 1,653 IU vitamin D; 66 IU vitamin E; 3.3 mg vitamin K; 0.033 mg vitamin B12; 24.8 mg niacin; 27.6 mg pantothenic acid; 8.27 mg riboflavin; 0.22 mg biotin; 2.2 mg folic acid; and 0.99 mg pyridoxine.

[6]Trace mineral premix (SEM Minerals, L.P., Quincy, IL) did not contain Se and provided per kg of diet: 161 mg Zn, 134 mg Fe, 42 mg Mn, 14 mg Cu, 0.66 mg Cl, and 9.0 µg Cr.

[7]Sodium selenite was used in phase 1 diet as the added Se source. Sodium selenite, Se yeast, and OH-SeMet were used as the added Se source in phase 2 and 3 diets as the 3 dietary treatments.

[8]STTD P = standardized total tract digestible phosphorus.

Table 2.2. Analyzed dietary Se and crude protein concentrations[1].

	Sodium selenite	Se yeast	OH-SeMet
Phase 1 (common)			
Se, mg/kg	0.514	---	---
Crude protein, %	18.6	---	---
Phase 2			
Se, mg/kg	0.552	0.588	0.616
Crude protein, %	19.9	20.5	20.5
Phase 3			
Se, mg/kg	0.414	0.548	0.549
Crude protein, %	19.0	19.8	19.0

[1]Sodium selenite was used in phase 1 diet as the added Se source. Sodium selenite, Se yeast, and OH-SeMet were used as the added Se source in phase 2 and 3 diets as the 3 dietary treatments. Feed samples were collected from at least 6 feeders per treatment per phase, pooled, and subsampled for Se concentration (MSU VDL) and crude protein (Kansas State University Swine Laboratory, Manhattan, KS).

Table 2.3. Evaluation of Se source on nursery pig growth performance[1,2].

	Sodium selenite	Se yeast	OH-SeMet	*P* =
d -7 to 0 (pre-treatment)[3]				
d -7 BW, kg	6.0 ± 0.05	6.0 ± 0.05	6.0 ± 0.05	0.979
d 0 BW, kg	6.6 ± 0.08	6.6 ± 0.08	6.6 ± 0.08	0.485
ADG, g	97 ± 6.2	93 ± 6.2	93 ± 6.2	0.367
ADFI, g	107 ± 3.6	103 ± 3.6	102 ± 3.6	0.097
G:F, g/kg	884 ± 33.8	897 ± 33.8	898 ± 33.8	0.815
d 0 to 14				
d 14 BW, kg	12.7 ± 0.07	12.7 ± 0.07	12.6 ± 0.07	0.121
ADG, g	435 ± 3.0[a]	432 ± 3.0[a]	422 ± 3.0[b]	0.003
ADFI, g	490 ± 3.2[a]	490 ± 3.1[a]	479 ± 3.2[b]	0.015
G:F, g/kg	888 ± 4.7	883 ± 4.6	884 ± 4.6	0.623
d 14 to 35				
d 35 BW, kg	26.9 ± 0.11	26.7 ± 0.11	26.7 ± 0.11	0.312
ADG, g	672 ± 4.4	664 ± 4.3	666 ± 4.4	0.328
ADFI, g	956 ± 7.8	940 ± 7.7	945 ± 7.8	0.176
G:F, g/kg	703 ± 3.0	707 ± 3.0	705 ± 3.0	0.352
d 0 to 35				
ADG, g	577 ± 3.0[x]	571 ± 2.9[xy]	567 ± 2.9[y]	0.066
ADFI, g	769 ± 4.8	759 ± 4.8	756 ± 4.8	0.100
G:F, g/kg	750 ± 2.1	752 ± 2.1	750 ± 2.1	0.560
d -7 to 35				
ADG, g	494 ± 2.5	490 ± 2.5	487 ± 2.5	0.110
ADFI, g	656 ± 3.9[x]	647 ± 3.9[xy]	645 ± 3.9[y]	0.090
G:F, g/kg	754 ± 2.2	757 ± 2.2	755 ± 2.2	0.450
Treatments, %[4]	4.6 ± 0.78	3.9 ± 0.78	5.8 ± 0.78	0.196
Removal, %[5]	2.65 ± 0.495	2.58 ± 0.487	2.94 ± 0.528	0.824
Mortality, %[6]	0.39 ± 0.172	0.39 ± 0.172	0.46 ± 0.189	0.939
Removal with mortality, %[7]	3.18 ± 0.509	3.11 ± 0.503	3.56 ± 0.540	0.781

[1]A total of 3,888 pigs (initially 6.0 ± 0.23 kg) was used with 54 pigs per replicate and 24 replicates per treatment. All pigs were fed 0.68 kg per pig of phase 1 common starter pellet that contained 0.3 mg/kg of added Se from sodium selenite for approximately 7 d. Phase 2 and phase 3 treatment diets were fed after pigs finished the phase 1 feed budget. All treatment diets provided 0.3 mg/kg added Se from sodium selenite, Se yeast, or hydroxy-selenomethionine ().

[2]BW = body weight. ADG = average daily gain. ADFI = average daily feed intake. G:F = feed efficiency.

[3]Day -7 to 0 ADFI was used as a covariate for growth performance in subsequent periods and overall growth performance.

[4]The number of injectable treatments given when pigs were on treatment diet divided by the number of pigs on d 0.

[5]The number of pigs removed based on body condition, lameness, and health status when they were on treatment diet divided by the number of pigs on d 0.

[6]The number of pigs found dead when they were on treatment diets divided by the number of pigs on d 0.

[7]The number of pigs removed or dead when they were on treatment diets divided by the number of pigs on d 0.

[a,b] Means within a row with different superscripts differ ($P \leq 0.05$).

[x,y] Means within a row with different superscripts differ ($0.05 < P \leq 0.10$).

Table 2.4. Evaluation of selenium source on nursery pig serum and tissue selenium concentrations and serum antioxidant status[1].

				P =		
	Sodium selenite	Selenium yeast	OH-SeMet	Source × day	Source	Day
Serum selenium, ng/mL[2]				0.072	0.002	< 0.0001
d 14	131 ± 3.7^{cd}	122 ± 3.7^{d}	139 ± 3.7^{c}			
d 35	184 ± 3.7^{b}	184 ± 3.7^{b}	205 ± 3.7^{a}			
Liver selenium, µg/g				---	< 0.0001	---
d 35	1.97 ± 0.049^{b}	1.99 ± 0.049^{b}	2.45 ± 0.049^{a}			
Muscle selenium, µg/g				---	< 0.0001	---
d 35	0.81 ± 0.024^{b}	0.87 ± 0.024^{b}	1.42 ± 0.024^{a}			
Serum GSH-Px, nmol/min/mL[3]				0.710	0.971	0.074
d 14	869 ± 129	888 ± 129	881 ± 129			
d 35	1,268 ± 128	1,210 ± 128	1,239 ± 128			
Serum T-AOC, CRE[4]				0.027	0.306	0.089
d 14	359 ± 22.9	389 ± 22.9	385 ± 22.9			
d 35	440 ± 22.9	470 ± 22.9	417 ± 22.9			
TBARS, µM MDA[5]				0.262	0.177	0.781
d 14	5.92 ± 0.97	5.25 ± 0.97	6.34 ± 0.97			
d 35	5.52 ± 0.97	4.28 ± 0.97	4.58 ± 0.97			

[1]A total of 3,888 pigs (initially 6.0 ± 0.23 kg) was used with 54 pigs per replicate and 24 replicates per treatment. All pigs were fed 0.68 kg per pig of phase 1 common starter pellet that contained 0.3 mg/kg of added selenium from sodium selenite for approximately 7 d. Phase 2 and phase 3 treatment diets were fed after pigs finished the phase 1 feed budget. All treatment diets provided 0.3 mg/kg added selenium. Selenium concentrations for serum, liver, and muscle were analyzed at MSU VDL.

[2]Day 0 serum samples were collected when all pigs were fed the phase 1 common diet and averaged 125 ng/mL across all treatments. Day 0 serum selenium concentration was used as a covariate for statistical analysis of d 14 and 35 serum selenium concentration as repeated measurement.

[3]GSH-Px = Glutathione peroxidase. One unit is defined as the amount of enzyme that causes the oxidation of 1.0 nmol of NADPH to $NADP^+$ per minute at 25°C.

[4]T-AOC = Total antioxidant capacity. CRE = µM Copper Reducing Equivalents.

[5]Thiobarbituric acid reactive substances. µM of MDA (malondialdehyde) equivalent.

[a,b,c,d] Means within a response with different superscripts differ ($P \leq 0.05$).

Chapter 3 - Polyphenols as a partial replacement for vitamin E in nursery pig diets.

Abstract

A total of 300 pigs (241 × 600; DNA, Columbus, NE; initially 6.0 ± 0.01 kg) were used in a 42-d trial to determine the effects of vitamin E levels and partially replacing vitamin E with a polyphenol (Cabanin CSD, R2 Argo, Denmark) on growth performance, complete blood count (CBC), serum thiobarbituric acid reactive substances (TBARS), superoxide dismutase (SOD), and cytokine panel. Sixty pens of pigs were weighed and allotted to 1 of 5 dietary treatments in a completely randomized design with 12 pens per treatment. A control treatment was formulated to provide 15 IU/kg of vitamin E equivalence from vitamin E. This control treatment was then used as a base for 3 replacement strategy diets to determine the effects of replacing an additional 60 IU/kg of vitamin E with polyphenol in diets containing a basal level of vitamin E requirement estimate (15 IU/kg). First, an additional 60 IU/kg of vitamin E was added for a total of 75 IU/kg of vitamin E equivalence. Second, 50% of the additional vitamin E (30 IU/kg) was replaced with the equivalency of polyphenol. Third, all 60 IU/kg of the additional vitamin E was replaced with the equivalency of polyphenol. To evaluate whether there are negative effects of feeding nursery pigs a high level of polyphenol, a fifth treatment was formulated to provide 575 IU/kg of vitamin E equivalence with 75 IU/kg from vitamin E and 500 IU/kg from polyphenol. Whole blood and serum samples were collected on d 10 and 42. For growth performance, increasing vitamin E equivalence tended to improve (quadratic, $P < 0.10$) G:F from d 10 to 21, and tended to improve (linear, $P < 0.10$) G:F from d 21 to 42 and 0 to 42. For antioxidant status, increasing vitamin E equivalence improved (linear, $P < 0.05$) d 42 SOD. For cytokine, there was no evidence of differences ($P > 0.10$) between treatments and vitamin E equivalence. Moreover, there was no

evidence of differences ($P > 0.10$) in all response variables between the 3 replacement strategies throughout the entire periods. In summary, increasing vitamin E equivalence tended to improve G:F, which may be related to the improved SOD activity. Furthermore, polyphenol can effectively replace vitamin E provided above the vitamin E requirement to provide similar benefits from increasing vitamin E equivalence.

Introduction

Weaning is a stressful period for piglets due to changes in diet composition, environment, and bacterial challenges, which results in reduced feed intake and growth rate (Campbell et al., 2013). During stressful periods, the need for antioxidants increases because of the increased oxidative stress (Hao et al., 2021). Oxidative stress is caused by the imbalance of excess formation of oxidants [free radicals, such as reactive oxygen species (ROS)] and insufficient degradation of these radicals by the animal's antioxidant system (Lü et al., 2010; Gessner et al., 2017; Hao et al., 2021). High ROS levels damage the cellular components, such as DNA, protein, and lipid, which cause gene mutation, abnormal signaling pathways, energy metabolism disorder, lipid peroxidation, and protein structure change (Lü et al., 2010; Hao et al., 2021). Moreover, during the weaning period, a local inflammation occurs in the small intestine, which can be characterized by increased cytokine levels and adverse effects on intestinal morphology, such as villus height, crypt depth, brush border enzyme activity, absorption capacity, and intestinal barrier integrity (Pié et al., 2004; Zheng et al., 2021). As a result, the combination of high oxidative stress and local inflammation from weaning in the small intestine can negatively affect growth performance.

Antioxidants neutralize free radicals by electron donation, complex formation between oxidizing elements, or the regeneration of other antioxidants (Lü et al., 2010). Besides

endogenous enzymatic antioxidants [e.g., superoxide dismutase (SOD), catalase, glutathione peroxidase], natural non-enzymatic antioxidants can also be involved (e.g., vitamin E and C, carotenoids, polyphenols) in protecting the cells from free radicals (Lü et al., 2010; Gessner et al., 2017; Hao et al., 2021).

Vitamin E is a fat-soluble vitamin that can be found in feed ingredients (green plants or seeds) as natural vitamin E (RRR-α-tocopheryl acetate); however, natural vitamin E is destroyed rapidly through oxidation under the influence of heat, moisture, rancid fat, or trace minerals (NRC, 2012). Thus, synthetic vitamin E (DL-α-tocopheryl acetate) has also been used to meet the vitamin E requirement estimate of the pigs (NRC, 2012). For nursery pigs, the vitamin E requirement estimate is 16 IU/kg (mg/kg) of the complete diet (NRC, 2012). However, surveys of industry nutritionists reported that their typical commercial US nursery diets contained approximately 75, 66, and 45 IU/kg of vitamin E for phase 1 , 2, and 3 diet, respectively (Flohr et al., 2016; Faccin et al., 2023). These above-requirement levels of vitamin E suggest a belief that providing extra antioxidant support will help the pigs overcome oxidative stress from the weaning process. Nonetheless, the effect of this higher level of dietary vitamin E compared to the NRC (2012) vitamin E requirement estimate on nursery pigs is not well understanded.

Another type of antioxidant that has been used in swine diets is plant-based polyphenols derived from the fruit and plant byproduct industry. These polyphenols are secondary plant metabolites that consist of a diverse group of compounds, including phenolic acids, flavonoids, tannins, and other phenolics (Naczk and Shahidi, 2006). They have shown some antioxidative and anti-inflammatory properties in several in vitro and in vivo studies and have the potential to partially replace vitamin E in swine, poultry, or dairy cow diets (Gessner et al., 2017; Lipiński et al., 2017). However, the effects of dietary polyphenols on nursery pigs' growth performance,

antioxidant status (TBARS and SOD), complete blood count, and cytokine panels have not been well investigated. Cabanin CSD (R2 Argo, Denmark) is a natural plant-based polyphenol product that contains selected extracts from grapes, citrus, blackcurrant, and chestnuts. These ingredients contain high concentrations of polyphenols; therefore, we hypothesized that this polyphenol product could potentially be used as an effective antioxidant replacer above the minimum NRC (2012) vitamin E requirement estimate for nursery pigs with no negative effects.

The objectives of this experiment were to evaluate the effects of vitamin E equivalence levels (15, 75, and 575 IU/kg), and vitamin E replacement strategies of replacing 60 IU/kg of vitamin E with polyphenol in diets above the minimum vitamin E requirement on growth performance, antioxidant status (TBARS and SOD), complete blood count, and cytokine panels of nursery pigs from weaning to 42 d post-weaning.

Material and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Two nursery rooms were used in this trial with 30 pens per room. Pigs were housed in pens with each pen (1.5 × 1.5 m) equipped with a 4-hole dry self-feeder, and a nipple waterer to provide *ad libitum* access to feed and water. A total of 300 pigs (241 × 600, DNA, Columbus, NE; initially 6.0 ± 0.01 kg) were weaned at approximately 21 d of age and placed in pens of 5 pigs each based on initial BW and gender. Pens of pigs were then randomly allotted to the 5 treatments in a completely randomized design with 12 replicate pens per treatment. The gender was balanced between dietary treatments.

Diets

The vitamin E form (44,092 IU/kg, DSM, Parsippany, NJ) used in this trial was DL-α-tocopherol acetate with 1 mg providing 1 IU of vitamin E equivalence. The natural polyphenol-based product (Cabanin CSD, R2 Argo, Denmark; Lot number: 220120) contained selected extracts from grapes, citrus, blackcurrant, and chestnuts. These ingredients contained high concentrations of polyphenols in the form of phenolic acids, flavonoids, and tannins, which have shown great antioxidative activity in in vitro studies (Naczk and Shahidi, 2006). The polyphenol product was assumed to have a 50% equivalency to vitamin E (DL-α-tocopherol acetate) based on a previous university trial conducted at Freie Universität Berlin (Germany) for weaned pigs (data not published). One mg of this polyphenol product provided 0.5 IU of vitamin E equivalence. The total polyphenol content was 9.2 % for this specific lot of polyphenol product used in this trial. A control treatment was formulated to provide 15 IU/kg of vitamin E equivalence from vitamin E to meet the requirement estimate for vitamin E. This control diet with 15 IU/kg of vitamin E was then used as the basal diet for three replacement strategy diets (Table 3.1). First, an additional 60 IU/kg of vitamin E was added for a total of 75 IU/kg of vitamin E equivalence. Second, 50% of the additional vitamin E (30 IU/kg) was replaced with the vitamin E equivalence from polyphenol. Third, all 60 IU/kg of supplemental vitamin E was replaced with the equivalency of polyphenol. These three replacement strategies allowed us to determine the effects of replacing vitamin E with polyphenol at different ratios for the additional 60 IU/kg of vitamin E equivalence added to diets containing a minimum vitamin E requirement estimate (15 IU/kg). The fifth treatment was formulated to provide a total of 575 IU/kg of vitamin E equivalence with 75 IU/kg from vitamin E and 500 IU/kg from polyphenol to evaluate whether there are negative effects of feeding nursery pigs a high level of polyphenol. Treatment

diets were fed in 3 phases based on bodyweight (phase 1: 6- to 7-kg; phase 2: 7- to 12-kg; and phase 3: 12- to 25-kg) in meal form.

Basal diets for all 3 phases (Table 3.2) were manufactured at Hubbard Feeds, Beloit, KS. The basal diets were mixed with remaining ingredients (e.g., vitamin E-free vitamin premix, vitamin E, and/or polyphenol) at the Kansas State University O.H. Kruse Feed Technology Innovation Center (Manhattan, KS) to make the 5 treatment diets. The remaining ingredients were mixed thoroughly for each dietary treatment before mixing with the basal diet. All diets met or exceeded the NRC (2012) nutrient requirement estimates, except for the low vitamin E treatment diet (15 IU/kg of vitamin E) and the phase 1 Lys level, which was formulated at 1.35% SID Lys for all treatments. Diet samples were collected and thoroughly mixed within treatment before analysis for vitamin E concentration with HPLC at the Colorado State University Veterinary Diagnostic Laboratory (Fort Collins, Colorado).

Data and sample collection

Pen weights and feed disappearance were measured on d 0, 10, 21, 31, 38, and 42 to determine ADG, ADFI, and G:F. The pigs were healthy as there were few medical treatments and no mortality throughout the 42-d trial. Whole blood and serum samples were collected from 1 median-weight pig of each pen on d 10 and 42 of the experiment for complete blood count (CBC), serum SOD activity, serum thiobarbituric acid reactive substances (TBARS), and serum cytokine panel. The same pig per experimental unit was used in all subsequent whole blood and serum collections. The gender of the selected pigs was balanced between treatments. Whole blood samples were collected with EDTA containing blood tubes (VACUETTE tube 6 ml K3E K3EDTA separator 13 × 100, non-ridged; Greiner Bio-One North America Inc., Monroe, NC) and analyzed for CBC at the Kansas State University Veterinary Diagnostic Laboratory

(Manhattan, KS) using an Advia 2120 hematology analyzer (Siemens Healthineers, Malvern, PA). For serum samples, whole blood was collected with blood collection tubes (Covidien Monoject blood collection tubes, silicone-coated tubes with red stoppers, no additive, 7 mL draw; Medtronic, Minneapolis, MN) that contained no anticoagulant or preservative, and allowed to clot for at least 30 min, centrifuged at 1,500 × g for 30 min, and the resulting serum supernatants were divided into 4 polypropylene tubes (PR1MA microcentrifuge tubes, natural boil-proof; Midwest Scientific, St. Louis, MO) as aliquots, and stored at -80°C. Serum cytokine panel (GM-CSF, IFNγ, IL-1α, IL-1ra, IL-1β, IL-2, IL-4, IL-6, IL-8, IL-10, IL-12, IL-18, TNFα) was evaluated at Eve Technologies (Calgary, AB, Canada). Serum TBARS and SOD were evaluated at the Kansas State University Swine Nutrition Laboratory (Manhattan, KS). For serum TBARS, the assay used in the experiment was described in Rao et al. (2021) and the samples were run in triplicate in 96-well microplates with intra-assay CV of ≤ 5.0%. For serum SOD, assay kits were purchased from Cayman Chemical Company (Ann Arbor, MI; # 703102) and samples were run in triplicate in 96-well microplates with intra-assay CV of ≤ 5.0%.

Statistical analysis

Data were analyzed as a completely randomized design for one-way ANOVA using the lmer function from the lme4 package for growth performance and blood parameters (CBC, cytokine panel, SOD, and TBARS) in R program (R Core Team, 2022). Pen was considered the experimental unit. Treatment was used as the fixed effect. Room was included in the model as a random intercept. Polynomial contrasts were constructed to evaluate the linear and quadratic effects of increasing vitamin E equivalence levels (15, 75, and 575 IU/kg) for all response criteria. Contrast coefficients were adjusted for unequally spaced treatments. Interactive effects of vitamin E equivalence levels × day (d 10 and 42) interaction and dietary treatment × day (d 10

and 42) interaction were tested for blood parameters. For serum cytokine data, the data were analyzed with the raw fluorescence intensity value based on Breen et al. (2015) with a log10 transformation for statistical analysis. All serum samples were analyzed at the same time with a single standard curve for each cytokine criteria. For serum TBARS and SOD assay, microtiter plate was used in the model as a random intercept. A Tukey multiple comparison adjustment was used, and all results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results

Growth performance

There was no evidence of differences ($P > 0.10$) in ADG and ADFI as vitamin E equivalence increased or between replacement strategies throughout the entire 42-d experimental period (Table 3.3). From d 10 to 21, increasing vitamin E equivalence increased (quadratic, $P = 0.086$) G:F from 15 to 75 IU/kg of vitamin E equivalence with no further increase at 575 IU/kg. From d 21 to 42, there was a tendency of improvement (linear, $P = 0.063$) in G:F as the vitamin E equivalence increased. This tendency of increasing improvement in G:F was also observed in overall (d 0 to 42) G:F (linear, $P = 0.075$).

Antioxidant status (TBARS and SOD)

For serum TBARS, there was no evidence of vitamin E equivalence × day interaction, treatment × day interaction, vitamin E equivalence effect, treatment effect, or day effect ($P > 0.10$; Figure 3.1). However, there was a vitamin E equivalence × day interaction ($P = 0.050$) on serum SOD activity (Figure 3.2). Increasing vitamin E equivalence increased (linear, $P = 0.036$) serum SOD activity on d 42 but not on d 10 (linear, $P = 0.616$). Moreover, there was no

treatment effect, day effect, or treatment × day interaction ($P > 0.10$) in serum SOD activity between the five dietary treatments on d 10 and 42.

Complete blood count

All CBC variables were approximate to or within the reference intervals for these ages of pigs according to the Iowa State University Clinical Pathology Laboratory reference intervals for swine (ISU, 2011). There was no evidence ($P > 0.10$) of vitamin E equivalence × day interaction and treatment × day interaction for all CBC criteria (Table 3.4). Increasing vitamin E equivalence tended to increase (quadratic, $P = 0.070$) leukocyte concentration and increased (quadratic, $P = 0.045$) eosinophil concentration from 15 to 75 IU/kg of vitamin E equivalence then reduced at 575 IU/kg. Additionally, there was a tendency (Treatment, $P = 0.089$) of treatment difference in segmented neutrophil concentration; however, no pairwise mean separation was observed. Lymphocyte and monocyte concentration were increased (Day, $P < 0.05$); platelets and segmented neutrophil concentration showed a tendency to increase (Day, $P < 0.10$), while RBC distribution width was decreased (Day, $P < 0.001$) from d 10 to 42.

Serum cytokines

There was no evidence of vitamin E equivalence × day interaction, vitamin E equivalence effect, treatment × day interaction, or treatment effect ($P > 0.10$) for any measured cytokine (Table 3.5). Even though there were no statistical differences, several proinflammatory cytokines showed numeric reduction in pigs fed diets formulated with 75 or 575 IU/kg of vitamin E equivalence compared to the control diet (15 IU/kg). Moreover, cytokine IL-1α, IL-2, IL-4, and IL-6 were increased (Day, $P < 0.05$); IL-1β, IL-10, and IL-12 showed a tendency to increase (Day, $P < 0.10$), and GM-CSF showed a tendency to decrease (Day, $P = 0.069$) from d 10 to 42.

Discussion

Although vitamin E and polyphenols are both added to swine diets for their antioxidative properties, their mechanism of action are different. Vitamin E can be absorbed in the intestine and enter the systemic circulation, as supplementing vitamin E in pig diets has shown increased serum and tissue (loin muscle, liver, and fat) vitamin E concentrations throughout the literature (Lauridsen, 2010; Song et al., 2014; Rey et al., 2017). The absorbed vitamin E can be used directly as antioxidants in the animals at cell membrane level, and also has a structural role in the cell membranes (NRC, 2012). On the other hand, there are few in vivo swine studies on the digestibility and bioavailability of polyphenols. Several human research studies suggest that only low percentages of the dietary polyphenols may be absorbed in the small intestine and had low bioavailability because of their molecular structures (Han et al., 2007; Landete, 2013; Faria et al., 2014). The polyphenols are expected to have direct antioxidant effects in vivo in the intestinal lumen because of the higher concentration of polyphenols in the lumen compared to the systemic concentrations (Gessner et al., 2017). Moreover, the low amount of absorbed polyphenols are then extensively bio-transformed in the liver and rapidly excreted in urine and bile (Hackman et al., 2008). Next, the bile-excreted polyphenol metabolites and the unabsorbed polyphenols are bio-transformed by the colon microbiota's enzymatic activities to various metabolites (Hein et al., 2008; Gessner et al., 2017). These bio-transformed polyphenol metabolites have shown prebiotic effects as growth-promoting substrates or antimicrobial substances for bacteria of the colon microbiota in human and mice research (Gessner et al., 2017). As these experiments were conducted on other monogastric species, more swine research is needed to determine whether this physiological process occurs similarly in pigs. Although there was no analytical data of the bio-transformed polyphenol metabolites, several swine research found feeding polyphenols

modulated the nursery pigs' microbiota composition (Ao et al., 2022; Wei et al., 2022; Xu et al., 2022), lowered the diarrhea incidence rate (Liu et al., 2021; Xu et al., 2022), and improved intestine barrier integrity (Hu et al., 2020; Chen et al., 2022; Guo et al., 2022). These improvements in gastrointestinal health from feeding polyphenols can potentially be a key mechanism of action in improving the overall health status, such as growth performance, systemic antioxidant status, and immune system of the nursery pigs.

Because the cell structural need for the lipophilic vitamin E and pigs cannot synthesize vitamin E endogenously (NRC, 2012), polyphenols, which are relatively hydrophilic (Tsao, 2010), theoretically cannot completely replace vitamin E in the diets (Gessner et al., 2017). Thus, our treatment diets all contained a minimum basal level of vitamin E equivalence (15 IU/kg) from vitamin E to meet the baseline requirement of vitamin E. This design allowed us to determine the effect of replacing vitamin E with polyphenols for the additional vitamin E equivalence above vitamin E requirement. In our study, we found no evidence of difference in ADG and ADFI throughout the 42-d experimental period; however, G:F was improved as vitamin E equivalence increased in our trial. Moreover, the three vitamin E replacement strategies showed similar results in all response variables, which suggests that polyphenol can effectively replace vitamin E for the additional 60 IU/kg of vitamin E equivalence in nursery pig diets that contained a baseline requirement (15 IU/kg) of vitamin E. Similar to our results, some studies found improved G:F with no evidence of difference in ADG and ADFI when additional vitamin E (Wilburn et al., 2008) or polyphenols (Fiesel et al., 2014; Silva-Guillen et al., 2020) were added to the nursery pig diets contained above requirement level of vitamin E. Differently, some studies found polyphenols improved nursery pigs' ADG or ADFI but not G:F (Dell'Anno et al., 2020; Liu et al., 2021; Ao et al., 2022). The improvement in growth performance in our

trial and other experiments may be related to the improvement in antioxidant and immune function. We found increasing vitamin E equivalence increased serum SOD activity. Similar to our results, several studies also found improved ($P \leq 0.05$) antioxidant status indicated by improved SOD, total antioxidant capacity (TAOC), and TBARS when nursery pigs were supplemented with vitamin E (Rey et al., 2017; Silva-Guillen et al., 2020) or polyphenols (Ao et al., 2022; Guo et al., 2022; Wei et al., 2022). For the immunes function, even though we only found some numerical reduction, many studies found significant reductions in proinflammatory cytokines, such as TNF-α, NF-kB, IL-1β, IL-1ra, IL-2, IL-4, IL-6, or IL-8, when vitamin E (Silva-Guillen et al., 2020) or polyphenols were fed to the nursery pigs (Fiesel et al., 2014; Pistol et al., 2019; Guo et al., 2022). A reduction in proinflammatory cytokine level in health pigs indicates an improvement in immune status, which suggests that these pigs may be able to spend less energy and AAs on immune overexpression which can potentially lead to an improved energy and AAs utilization (Gessner et al., 2017). This may explain the reduced cytokines and improved feed efficiency found in several experiments cited above. Moreover, we found several cytokines (GM-CSF, IL-1α, IL-1β, IL-2, IL-4, IL-6, IL-10, and IL-12) increased from d 10 to 42 as nursery pig aged. Though there are no reference values for cytokine level based on pig's age, some evidences suggest that cytokine levels tend to increase as weaned pigs age (de Groot et al., 2005). For the results of CBC, we observed some differences as the vitamin E equivalence increased (leukocyte and eosinophil) or between dietary treatments (segmented neutrophil); however, whether these differences affected growth performance are not clear as all CBC variables were within the reference intervals for these ages of pigs (ISU, 2011) . There is some evidence suggesting that some CBC parameters are associate with growth performance for grow-finish pigs (Lindholm-Perry et al., 2021); nevertheless, more research is needed for nursery pigs.

Additionally, we found lymphocyte, monocyte, platelets, and segmented neutrophil increase, while RBC distribution width decreased from d 10 to 42. These differences between days can be expected as pigs age (ISU, 2011).

Though some studies found no evidence of difference ($P > 0.10$) in growth performance (ADG, ADFI, and G:F) following the inclusion of dietary vitamin E (Kim et al., 2016; Rey et al., 2017; Chen et al., 2019) or polyphenols (Zhang et al., 2014; Xu et al., 2019; Hu et al., 2020) in the nursery pig diets, several of these studies found improvement in antioxidant status (TBARS and T-AOC) or gastrointestinal health (tight junction), or reduced cytokines (TNF-α, IL-1β, IL-2, or IL-6). This lack of differences in growth performance may be attributed to the lack of sufficiently stressful events that would generate high levels of oxidative stress that allow the improved antioxidant and immune status to demonstrate their beneficial effects on growth. Many of these studies were conducted in high-health-status farms, where the barn environment was highly regulated, and exposure to environmental pathogens was minimized, thereby reducing the challenges that can increase oxidative stress or trigger immune responses in these weaned pigs. Dietary vitamin E or polyphenol levels in these experimental diets might have already provide sufficient antioxidative or immune promoting effects to optimize the growth performance of these nursery pigs; thus, no evidence of differences in growth was be found. To understand the effects of vitamin E and polyphenols fed to pigs under higher oxidative stress, controlled challenged experiments may have the potential to provide us some insights as they can increase the oxidative stress of pigs (Hao et al., 2021). Jiang et al. (2014) found E. coli challenged nursery pigs fed polyphenols had improved G:F, GSH-Px, and T-AOC compared to the E. coli challenged pig without polyphenols. Chen et al. (2022) found diquat-challenged nursery pigs fed polyphenols had improved ADG, antioxidant status, and intestinal barrier integrity compared to

challenged pigs without polyphenols in the diet. For nursery pigs challenged with LPS, dietary polyphenols reduced TBARS and cytokines, and improved intestine tight junction (Hu et al., 2020; Hu et al., 2022). These results suggest that pigs under high oxidative stress from controlled challenges could benefit from supplementing vitamin E and polyphenols in the diets for growth, antioxidant status, and health. However, more research is needed as only few research has been conducted for pigs under controlled oxidative stress.

Additionally, comparing the results of different polyphenol experiments on nursery pigs poses challenges due to the diversity of polyphenols used as feed additives. These polyphenol additives are derived from various fruits and herbs extracts, and combined in different ratios. The scientific literature lacks a thorough investigation of whether different polyphenols exert distinct or similar effects on nursery pigs' growth, antioxidant status, or immune system. Furthermore, the inclusion levels of these polyphenol additives vary widely from 0.01 to 10% with difference concentrations and compositions of polyphenol content. Similarly, the effects of vitamin E on nursery pigs may also be variable, since the natural vitamin E concentrations from feed ingredients vary as heat and humidity from environmental conditions could rapidly destroys them (NRC, 2012). Furthermore, vitamin E requirement can also be affected by many dietary factors, including Se, unsaturated fatty acids, and other natural or synthetic antioxidants (NRC, 2012). These factors all contributed to posing challenges in determining the effects of vitamin E and polyphenols on nursery pigs' performance.

In summary, increasing vitamin E equivalence by the addition of vitamin E or polyphenols improve feed efficiency, which may be related to the improved serum SOD activity. Moreover, we found no evidence of difference between the three vitamin E replacement strategies in all response criteria. Thus, this suggests that polyphenol can be used as an effective

replacement for the 60 IU/kg of additional vitamin E added to diets that met the basal vitamin E requirement (15 IU/kg) for nursery pigs. These similar improvements may be driven by different mechanism of actions between vitamin E and polyphenols. Lastly, whether different vitamin E levels or vitamin E replacement strategies can provide similar results in conditions that have higher oxidative stress or pathogen challenge requires further research.

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Table 3.1. Sources of treatment dietary vitamin E equivalence.

Vitamin E[1], mg/kg:	15	75	45	15	75
Polyphenol[2], mg/kg:	0	0	60	120	1,000
Vitamin E equivalence, IU/kg					
Vitamin E requirement	15	15	15	15	15
Additional vitamin E equivalence					
Vitamin E	0	60	30	0	60
Polyphenol	0	0	30	60	500
Total vitamin E equivalence[3]	15	75	75	75	575
Analyzed vitamin E, mg/kg[4]					
Phase 1	17.0	36.0	35.0	16.0	76.0
Phase 2	5.3	50.0	51.0	11.0	25.0
Phase 3	23.0	85.0	69.0	13.0	98.0
Weighted average[5]	16.9	64.2	56.2	13.2	73.6

[1] Vitamin E (44,092 IU/kg, DSM, Parsippany, NJ). The vitamin E form was DL-α-tocopherol acetate. One mg of DL-α-tocopherol acetate provides 1 IU of vitamin E equivalence.

[2] Cabanin CSD (R2 Argo, Denmark) was used as the polyphenol source in this trial and assumed to have a 50% equivalency to vitamin E. One mg of Cabanin CSD provides 0.5 IU of vitamin E equivalence.

[3] Total vitamin E equivalence is the combination of vitamin E equivalence provided by vitamin E and polyphenol.

[4] Vitamin E concentration was analyzed at Colorado State University Veterinary Diagnostic Laboratory (Fort Collins, Colorado).

[5] Weighted averages = Sum of the calculated vitamin E intake of the 3 phases / total feed intake.

Table 3.2. Diet composition, (as-fed basis)[1]

Item	Phase 1	Phase 2	Phase 3
Ingredients, %			
Corn	43.4	44.7	52.4
Soybean meal (46.5% CP)	20.6	26.4	29.1
Corn DDGS	5.0	10.0	15.0
Fish meal	2.5	--	--
Dried whey	10.0	--	--
Dried whey permeate (80% lactose)	10.0	--	--
Fermented soybean meal[2]	4.0	4.0	--
Choice white grease	1.0	1.0	--
Calcium carbonate	0.50	0.83	0.90
Monocalcium phosphate	0.80	0.90	0.70
Sodium chloride	0.30	0.50	0.60
L-Lys-HCl	0.45	0.45	0.45
DL-Met	0.22	0.19	0.11
L-Thr	0.18	0.17	0.15
L-Trp	0.03	0.02	0.03
L-Val	0.09	0.04	0.02
Trace mineral premix[3]	0.15	0.15	0.15
Zinc oxide	0.40	0.26	--
Phytase[4]	0.01	0.01	0.01
Vitamin premix[5]	0.11	0.11	0.11
Treatment premix[6]	0.29	0.29	0.29
Total	100.00	100.00	100.00
Calculated analysis			
SID AA, %			
Lys	1.35	1.35	1.30
Ile:Lys	58	61	61
Leu:Lys	117	127	137
Met:Lys	38	37	33
Met and Cys:Lys	56	56	56
Thr:Lys	63	63	63
Trp:Lys	19.0	19.1	18.9
Val:Lys	69	69	69
His:Lys	34	38	40
Net energy, kcal/kg	2,529	2,469	2,392
CP, %	21.4	22.9	23.0
Ca, %	0.67	0.67	0.64
STTD P, %	0.60	0.53	0.49

[1] Phase 1, 2, and 3 diets were formulated based on pig bodyweight (phase 1: 6- to 7-kg; phase 2: 7- to 12-kg; and phase 3: 12- to 25-kg) in meal form.

[2] MEpro (Prairie Aquatech, Brookings, SD).

[3] Trace mineral premix provided per kg of diet: 110 mg Zn, 110 mg Fe, 33 mg Mn, 16.5 mg Cu, 0.29 mg I, and 0.29 mg Se.

[4] Quantum Blue 5G (AB Vista, Plantation, FL) provided 626 FTU per kg of diet with an expected STTD P release of 0.15%.

[5] Vitamin premix without vitamin E provided per kg of diet: 4,134 IU vitamin A; 1,653 IU vitamin D; 3.3 mg vitamin K; 0.033 mg vitamin B_{12}; 49.6 mg niacin; 27.6 mg pantothenic acid; and 8.27 mg riboflavin.

[6] For the 5 treatments, treatment premix provided per ton of diet: 0.35, 1.7, 1.05, 0.35, and 1.7 kg of vitamin E (44,092 IU/kg, DSM, Parsippany, NJ), respectively; 2.35, 1.0, 1.6, 2.25, and 0.0 kg of ground corn, respectively; and 0.0, 0.0, 0.06, 0.12, 1.0 kg of polyphenol (Cabanin CSD, R2 Argo, Denmark), respectively.

Table 3.3. Evaluation of vitamin E levels and vitamin E replacement strategies on nursery pig growth performance[1,2]

Vitamin E, mg/kg	15	75	45	15	75			
Polyphenol, mg/kg	0	0	60	120	1,000		Probability, *P* =	
Total E equivalence, IU/kg	15	75	75	75	575	SEM	Linear[4]	Quadratic[4]
d 0 to 10 (Phase 1)								
d 0 BW, kg	6.0	6.0	6.0	6.0	6.0	0.01	0.998	0.803
d 10 BW, kg	7.4	7.2	7.2	7.4	7.3	0.11	0.945	0.451
ADG, g	140	128	125	139	137	11.3	0.943	0.429
ADFI, g	168	165	154	161	162	8.0	0.776	0.394
G:F, g/kg	824	771	807	858	835	42.3	0.678	0.693
d 10 to 21 (Phase 2)								
d 21 BW, kg	12.4	12.4	12.4	12.5	12.3	0.21	0.588	0.931
ADG, g	460	465	475	465	451	19.7	0.405	0.485
ADFI, g	591	584	585	576	567	20.1	0.244	0.670
G:F, g/kg	779	797	810	807	798	13.8	0.574	0.086
d 21 to 42 (Phase 3)								
d 42 BW, kg	25.1	25.3	25.5	25.8	25.2	0.38	0.867	0.319
ADG, g	604	617	620	633	614	12.2	0.878	0.159
ADFI, g	929	936	947	959	917	19.2	0.400	0.348
G:F, g/kg	649	660	657	660	670	7.3	0.063	0.337
d 0 to 42 (Overall)								
ADG, g	455	461	464	471	458	9.0	0.867	0.321
ADFI, g	659	660	663	669	646	13.0	0.317	0.655
G:F, g/kg	691	698	701	705	709	6.5	0.075	0.212

[1]A total of 300 pigs were used with 60 pigs per replicate and 12 replicates per treatment. Total E equivalence is the combination of vitamin E equivalence provided by vitamin E and polyphenol (Cabanin CSD, R2 Argo, Denmark).

[2] BW = body weight. ADG = average daily gain. ADFI = average daily feed intake. G:F = feed efficiency.

[3] Treatment was not significant, $P > 0.10$.

[4] Polynomial contrasts were utilized to analyze the effects of dietary total E equivalence levels (15, 75, and 575 IU/kg).

Table 3.4. Evaluation of vitamin E levels and vitamin E replacement strategies on nursery pig complete blood count[1]

Vitamin E, mg/kg		15	75	45	15	75					
Polyphenol, mg/kg		0	0	60	120	1,000		Probability, *P* =			
Total E equivalence, IU/kg		15	75	75	75	575	SEM	Treatment[2]	Day[2]	Linear[3]	Quadratic[3]
Erythrocyte, M/uL	d 10	6.33	6.38	6.20	6.34	6.29	0.118	0.818	0.456	0.770	0.492
	d 42	6.43	6.31	6.32	6.31	6.35					
Hemoglobin, g/dL	d 10	11.3	11.5	11.5	11.7	11.2	0.21	0.702	0.540	0.915	0.613
	d 42	11.5	11.3	11.7	11.4	11.7					
Mean cell volume, fL	d 10	60.3	60.9	62.5	62.1	60.4	1.06	0.244	0.530	0.828	0.163
	d 42	60.9	60.8	62.5	61.7	62.1					
Mean cell hemoglobin, pg	d 10	18.0	18.0	18.5	18.4	17.9	0.35	0.376	0.757	0.872	0.225
	d 42	17.9	17.9	18.6	18.2	18.3					
Mean cell hemoglobin, g/dL	d 10	29.8	29.5	29.6	29.7	29.6	0.25	0.970	0.230	0.977	0.938
	d 42	29.4	29.5	29.7	29.4	29.6					
Hematocrit, %	d 10	35.5	35.9	36.0	36.6	35.3	0.67	0.666	0.389	0.702	0.745
	d 42	36.3	35.3	36.5	35.8	36.2					
RBC distribution width, %	d 10	23.5	23.3	23.1	23.7	22.6	0.75	0.872	< 0.001	0.324	0.871
	d 42	18.9	18.4	18.2	19.2	18.2					
Leukocyte, K/uL	d 10	13.0	17.3	14.3	13.9	14.1	1.50	0.149	0.003	0.843	0.070
	d 42	18.1	19.7	19.3	20.0	19.0					
Segmented neutrophil, K/uL	d 10	5.47	8.53	6.5	5.7	5.84	0.919	0.089	0.081	0.812	0.329
	d 42	7.43	7.39	7.66	7.22	7.28					
Band neutrophil, K/uL	d 10	0.008	0.100	0.025	0.027	0.033	0.0402	0.527	0.456	0.716	0.354
	d 42	0.050	0.030	0.080	0.090	0.080					
Lymphocyte, K/uL	d 10	6.51	7.17	6.72	7.07	7.11	0.852	0.967	0.024	0.462	0.144
	d 42	8.8	10.3	10.0	10.6	10.0					
Monocyte, K/uL	d 10	0.67	0.95	0.75	0.67	0.70	0.15	0.667	< 0.001	0.345	0.748
	d 42	1.48	1.37	1.23	1.61	1.22					
Eosinophil, K/uL	d 10	0.24	0.52	0.29	0.41	0.34	0.084	0.163	0.833	0.885	0.045
	d 42	0.27	0.54	0.29	0.28	0.26					

Basophil, K/uL	d 10	0.06	0.03	0.08	0.02	0.05	0.038	0.753	0.426	0.934	0.587
	d 42	0.10	0.06	0.03	0.16	0.10					
Platelets, K/uL	d 10	342.2	430.2	378.5	395.9	310.7	53.03	0.315	0.068	0.117	0.207
	d 42	437.4	407.3	528.3	438.0	382.0					

[1] A total of 300 pigs (initially 6.0 kg) were used with 60 pigs per replicate and 12 replicates per treatment. Complete blood count was analyzed at Kansas State University Veterinary Diagnostic Laboratory (Manhattan, KS). Total E equivalence is the combination of vitamin E equivalence provided by vitamin E and polyphenol (Cabanin CSD, R2 Argo, Denmark).

[2] F-test *P*-value. All treatment × day interactions were not statistically significant ($P > 0.10$).

[3] Polynomial contrasts were utilized to analyze the effects of dietary total E equivalence levels (15, 75, and 575 IU/kg) of collection. All total E equivalence levels × day interactions were not statistically significant ($P > 0.10$).

Table 3.5. Evaluation of vitamin E levels and vitamin E replacement strategies on nursery pig cytokine profile (fluorescence intensity value)[1]

Vitamin E, mg/kg		15	75	45	15	75					
Polyphenol, mg/kg		0	0	60	120	1,000		Probability, *P* =			
Total E equivalence, IU/kg		15	75	75	75	575	SEM	Treatment[2]	Day[2]	Linear[3]	Quadratic[3]
GM-CSF	d 10	18.0	14.0	11.9	18.8	15.9	1.22	0.476	0.069	0.884	0.856
	d 42	12.2	11.6	11.7	20.0	12.7					
IFNγ	d 10	43.0	46.3	36.8	45.9	42.3	1.31	0.973	0.138	0.889	0.909
	d 42	28.5	30.2	23.7	39.7	32.0					
IL-1α	d 10	47.2	32.7	26.5	71.6	27.0	1.40	0.122	0.004	0.185	0.239
	d 42	162.3	114.9	97.3	79.7	101.8					
IL-1β	d 10	85.4	70.4	56.7	98.3	44.0	1.31	0.220	0.059	0.139	0.288
	d 42	163.5	123.6	103.8	95.9	120.1					
IL-1ra	d 10	359.1	274.0	310.0	464.1	291.9	1.25	0.127	0.631	0.268	0.377
	d 42	314.5	221.1	249.5	235.7	225.3					
IL-2	d 10	51.8	31.6	31.3	74.5	26.8	1.42	0.150	0.008	0.188	0.202
	d 42	166.8	94.4	105.8	81.3	107.1					
IL-4	d 10	71.2	53.0	40.7	98.1	39.6	1.40	0.128	0.020	0.101	0.267
	d 42	174.0	138.0	108.2	89.8	102.9					
IL-6	d 10	63.9	37.4	39.8	82.5	32.3	1.37	0.134	0.041	0.160	0.198
	d 42	147.8	112.0	92.1	76.7	104.0					
IL-8	d 10	680.5	583.7	437.7	674.5	654.6	1.37	0.849	0.166	0.565	0.770
	d 42	406.8	401.2	393.7	417.8	273.1					
IL-10	d 10	58.6	39.9	46.0	80.0	34.5	1.38	0.371	0.067	0.180	0.359
	d 42	125.7	79.5	79.7	72.5	76.1					
IL-12	d 10	612.2	700.3	757.3	774.1	644.3	1.16	0.757	0.064	0.119	0.711
	d 42	900.9	741.8	806.3	777.6	589.5					
IL-18	d 10	91.7	82.8	80.3	128.6	63.4	1.30	0.367	0.135	0.405	0.537
	d 42	148.2	109.9	99.8	107.0	129.8					
TNFα	d 10	37.2	31.4	27.6	32.9	34.1	1.22	0.872	0.132	0.690	0.741

d 42	26.9	23.6	24.3	44.4	32.9

[1] A total of 300 pigs (initially 6.0 kg) were used with 60 pigs per replicate and 12 replicates per treatment. Serum cytokine panel was evaluated at Eve Technologies (Calgary, AB, Canada). Data was log10 transformed for statistical analysis and transformed back for the cell mean values reported in this table. Total E equivalence is the combination of vitamin E equivalence provided by vitamin E and polyphenol (Cabanin CSD, R2 Argo, Denmark).

[2] F-test *P*-value. All treatment × day interactions were not statistically significant ($P > 0.10$).

[3] Polynomial contrasts were utilized to analyze the effects of dietary total E equivalence levels (15, 75, and 575 IU/kg) of collection. All total E equivalence levels × day interactions were not statistically significant ($P > 0.10$).

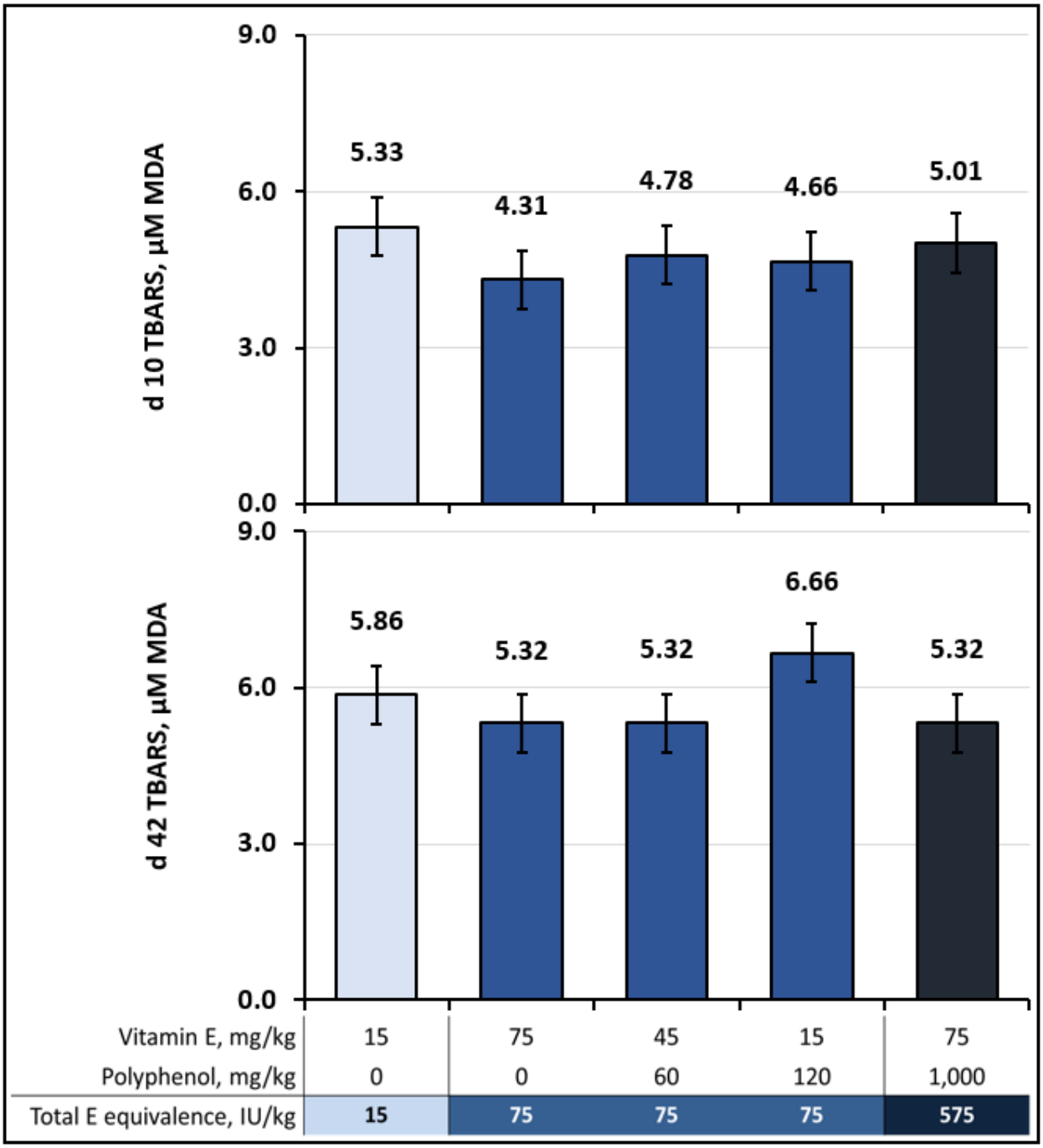

Figure 3.1. Serum TBARS concentration on d 10 and 42.

Error bar equals to 1 SEM. A total of 300 pigs (initially 6.0 kg) were used with 60 pigs per replicate and 12 replicates per treatment. Total E equivalence is the combination of vitamin E equivalence provided by vitamin E and polyphenol (Cabanin CSD, R2 Argo, Denmark). There was no evidence of total vitamin E equivalence × day interaction, vitamin E equivalence, treatment × day interaction, treatment, or day effect ($P > 0.10$).

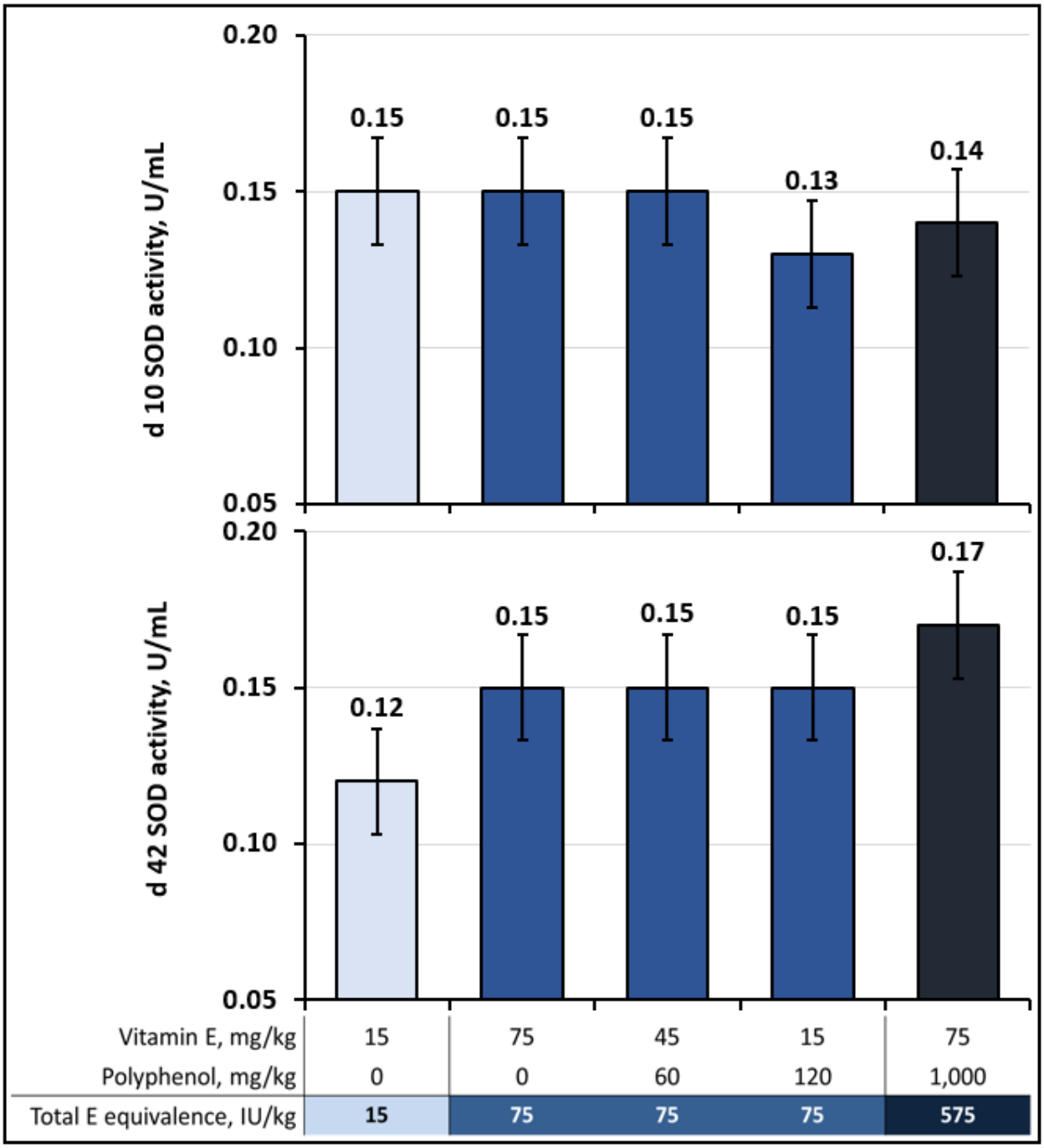

Figure 3.2. Serum SOD activity on d 10 and 42.

Error bar equals to 1 SEM. A total of 300 pigs (initially 6.0 kg) were used with 60 pigs per replicate and 12 replicates per treatment. Total E equivalence is the combination of vitamin E equivalence provided by vitamin E and polyphenol (Cabanin CSD, R2 Argo, Denmark). There was a total vitamin E equivalence × day interaction (linear interaction, $P = 0.05$), but no evidence of treatment × day interaction, treatment, or day effect ($P > 0.10$). Increasing total vitamin E equivalence increased SOD on d 10 (linear, $P = 0.036$) but not on d 42 (linear, $P = 0.616$).

Chapter 4 - Evaluation of nutritional strategies to slow growth rate then induce compensatory growth in 90-kg finishing pigs.

Abstract

Two 44-d experiments were conducted to evaluate nutritional strategies with different concentrations of dietary lysine (and other amino acids) on growth rate and subsequent compensatory gain of 90-kg finishing pigs. Three diets were formulated to contain 0.70 (control), 0.50% and 0.18% standardized ileal digestible (SID) Lys. In Exp. 1, 356 pigs (Line 241 × 600, DNA; initially 89.0 ± 1.10 kg) were used with four treatments. From d 0 to 28, pigs received either the control or the 0.50%-Lys diet. On d 28, pigs either remained on these diets or were switched the 0.18%-Lys diet until d 44. There were 18 pens per treatment from d 0 to 28 and 9 pens per treatment from d 28 to 44. From d 0 to 28, pigs fed the 0.50%-Lys diet had decreased ($P < 0.001$) ADG and G:F compared to those fed the control diet. From d 28 to 44, pigs switched to the 0.18%-Lys diet had decreased ($P < 0.05$) ADG and G:F compared to pigs that remained on the control or 0.50%-Lys diets. From d 0 to 44, pigs fed 0.50%-Lys diet for 44-d had decreased ($P < 0.05$) ADG, G:F, and percentage carcass lean compared to pigs fed the control diet. Pigs fed the 0.50%-Lys diet then the 0.18%-Lys diet had decreased ($P < 0.05$) ADG and G:F compared to other treatments. Pigs fed the 0.50%-Lys diet for 44-d and pigs fed the control diet then 0.18%-Lys diet had decreased ($P < 0.05$) ADG, G:F, and percentage carcass lean compared to control pigs. In Exp. 2, 346 pigs (Line 241 × 600, DNA; initially 88.6 ± 1.05 kg) were used to evaluate compensatory growth after varying durations of dietary lysine restriction. A total of four treatments were used including pigs fed the control diet for 44-d or fed the 0.18%-Lys diet for 14, 21, or 28-d and then fed the control diet until the conclusion of the experiment on d 44. There were nine pens per treatment. On average, pigs fed the 0.18%-Lys diet grew 49% slower than the

control. Compared to the control, ADG of pigs previously fed the 0.18%-Lys diet increased ($P < 0.05$) 28% during the first week after switching to the control diet and 12% for the rest of the trial. Despite this improvement, overall ADG, G;F, final BW, and percentage carcass lean decreased (linear, $P < 0.05$) as the duration of Lys restriction increased. In summary, feeding Lys restricted diets reduced the ADG and G:F of finishing pigs. Compensatory growth can be induced in Lys-restricted finishing pigs, but the duration of restriction and recovery influences the magnitude of compensatory growth.

Introduction

The U.S. pork industry experienced a substantial reduction in the ability to process market pigs due to packing plant closures attributed to the 2020 COVID-19 pandemic. With the reduced capacity for processors to accept market animals, pigs grew beyond their intended market weight making them too large for the infrastructure of the facility. Therefore, producers were forced to utilize a variety of strategies to reduce the growth rate of pigs and minimize economic hardship. Because lysine (Lys) is the first limiting amino acid (AA) for corn– soybean meal-based diets, reducing dietary SID Lys in the late-finishing period has been shown to reduce the ADG and ADFI of pigs beyond 100-kg body weight (Soto et al., 2019). Therefore, feeding finishing pigs SID Lys (as well as other AA) concentrations below their estimated requirements can reduce the growth rate, but the magnitude of the reduction is not fully researched. Recently, Helm et al. (2021) evaluated nutrient restriction to slow growth rate of finishing pigs in response to processing plant closures or reduced capacity. In that study, restricting Lys and other AAs dramatically decreased ADG and G:F. To the best of our knowledge, there is little additional information available in the literature regarding using severely deficient SID Lys concentrations as a nutritional strategy to intentionally limit the growth rate of late-finishing pigs. In addition, as

processing plants re-opened or increased their processing capability, pigs were often switched from the Lys-restricted corn-based diets formulated to restrict growth, to more standard diets with sufficient Lys concentrations to attempt to recover growth rates. For growing-finishing pigs, switching from Lys-restricted diets to Lys-sufficient diets can induce compensatory growth, a physiological process of animals having accelerated growth rate after a period of restriction (Hornick et al., 2000; Menegat et al., 2020). Therefore, our objectives were to determine the effects of feeding diets with severely deficient SID Lys and other AA concentrations to reduce growth rates, and second, to evaluate the effects of Lys-induced compensatory gain on growth performance and carcass characteristics of late-finishing pigs beyond 90-kg BW.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. These studies were conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The facility was totally enclosed and environmentally regulated. Each pen was equipped with a two-hole dry single-sided feeder (Farmweld, Teutopolis, IL) and a 1-cup waterer to provide ad libitum access to feed and water. Pigs were stocked at a floor space of approximately 0.65 m2 per pig for Exp. 1 and 0.74 m2 per pig for Exp. 2. Pens were equipped with adjustable gates to allow space allowances per pig to be maintained if a pig died or was removed from a pen during the experiment. Pens were located over a completely slatted concrete floor with a 1.2-m pit underneath for manure storage. A robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN) was used to deliver and record daily feed additions to each individual pen. At the initiation of the studies, pens of pigs were weighed and allotted to 1 of 4 treatments for each experiment in a randomized complete block

design with average pen weight serving as the blocking factor. Pigs were housed in mixed-gender pens with 9–10 pigs per pen. Pens of pigs were weighed approximately every 7 days from d 0 to 44 of the experiments to determine average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F). On the last day of both experiments, final pen weights were taken, and the remaining pigs were tagged with RFID ear tags and transported to a USDA-inspected packing plant (Triumph Foods, St. Joseph, MO) for carcass data collection. Carcass measurements included hot carcass weight (HCW), loin depth, backfat depth, and percentage lean.

Diets

A total of 3 diets were manufactured (control, 0.50%-Lys and 0.18%-Lys; Table 4.1). The control diet was corn–soybean meal-based and formulated to contain 0.70% SID Lys and 13.0% CP. The 0.50%-Lys diet included 5% soybean meal and contained 10.3% CP. The 0.18%-Lys diet was made up of 98% corn and 2% vitamins and minerals. It was calculated to have 8.1% CP and was the lowest SID Lys (and other AAs) concentration possible for an all corn-based diet. The control diet was formulated to meet requirement estimates established by NRC (2012) for pigs in this weight range. The other two diets were formulated to be deficient in SID Lys and other AAs to restrict growth rate. All diets met NRC (2012) requirement estimates for vitamins and minerals.

Experiment 1

A total of 356 pigs (Line 241 × 600, DNA; Columbus, NE; initially 89.0 ± 1.10 kg) were used with 4 treatments in a 44-d study. From d 0 to 28, pens of pigs were fed 1 of 2 dietary treatments (control or 0.50%-Lys; Figure 4.1). On d 28, pens of pigs previously fed the control diet were divided into two groups, half continued to be fed the control diet and the other half

were fed the 0.18%-Lys diet until d 44. Pens previously fed the 0.50%-Lys diet were divided into two groups, half continued to be fed the 0.50%-Lys diet and the other half were fed the 0.18%-Lys diet until d 44. On d 28, one or two of the heaviest pigs in each pen were selected and marketed resulting in 8 remaining pigs per pen until d 44. The adjustable gates were moved to maintain a constant floor space per pig when the heaviest pigs were removed. These pigs were included in the d 0–28 growth performance data but not carcass data.

Experiment 2

A total of 346 pigs (Line 241 × 600, DNA, Columbus, NE; initially 88.6 ± 1.05 kg) were used with 4 treatments in a 44-d study. The first treatment consisted of pigs fed the control diet from d 0 to 44 (Figure 4.2). For the other three treatments, pigs were fed the 0.18%-Lys diet for 14, 21, or 28 days and then switched to the control diet for the remainder of the trial. Thus, these treatment groups were fed the control diet for 30, 23, or 16 days prior to marketing, respectively. The restriction period was defined as the period when pigs were fed the 0.18%- Lys diet, and the recovery period was defined as the period when pigs were switched from the 0.18%- Lys diet to the control diet. Like Exp. 1, pigs were marketed for carcass data collection at the same packing plant; however, all pigs were marketed on d 44 (no pigs were marketed on day 28).

Economic Analysis

For both experiments, economic analysis including feed cost, feed cost per kg of gain, revenue per pig, and income over feed cost (IOFC) was calculated on a per pig placed basis. Ingredient cost (USD per kg) at the time of the study were used with corn valued at $0.12, soybean meal at $0.336, L-lysine HCl at $1.32, DL-methionine at $2.54, L-threonine at $1.76, and L-tryptophan at $8.82. Diet cost was $0.17 per kg for the control diet, $0.15 per kg for the 0.50%-Lys diet, and $0.14 per kg for the 0.18%-Lys diet. Feed cost per pig was calculated by

multiplying the diet cost per kg by ADFI and by the number of days in each period. Feed cost per kg of gain was calculated by dividing the feed cost per pig by the overall weight gain per pig. Revenue was obtained by multiplying HCW by either a low carcass market value ($0.66/ kg; low) or a more typical market value ($1.43/kg; standard). The IOFC was calculated by subtracting the feed cost per pig from revenue per pig.

Representative diet samples of both experiments were obtained from the feeders of each treatment, homogenized, and analyzed for dry matter (method 935.29; AOAC Int., 2019) and crude protein (method 990.03; AOAC Int., 2019; Ward Laboratories Inc., Kearney, NE; Table 4.1).

Statistical Analysis

Data were analyzed as a randomized complete block design for one-way ANOVA using the lme function from the nlme package (Pinheiro et al., 2020) in R program (R Core Team, 2019). Pen was considered the experimental unit, initial pen average BW as the blocking factor, and treatment as a fixed effect. For every response, two analytical models were constructed by assuming 1) equal variance across all treatments, or 2) assuming a unique estimate of variance for each treatment group. Similar procedures have been implemented by Rao et al. (2020a, 2020b) building upon the concepts outlined by Goncalves et al. (2016). Both models were fit, and model selection was based on the ANOVA test ($P \leq 0.05$) via Bayesian information criterion. Tukey adjustment was used for multiple comparisons using the emmeans package (Lenth, 2020). All results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$. For Exp. 1, data were analyzed as two treatments (control or 0.50%-Lys) with 18 pens per treatment from d 0 to 28 and as 4 treatments with 9 pens per treatment for d 28 to 44 and the overall period. For Exp. 2, data were analyzed as two treatments (control or 0.18%- Lys

diet) from d 0 to 14, 3 treatments from d 14 to 21, and 4 treatments from d 21 to 44, and d 0 to 44. Polynomial contrasts were constructed to evaluate the linear and quadratic effects for feeding duration of the 0.18%-Lys diet for d 28–44, and d 0–44.

Results

Experiment 1

From d 0 to 28, pigs fed the 0.50%-Lys diet had decreased ($P < 0.001$) ADG, G:F, d 28 BW, Lys intake per day, and Lys intake per kg of gain compared to pigs fed the control diet (Table 4.2). On d 28, one or two of the heaviest pigs in each pen were selected and marketed. Day 28 pre-marketing BW was approximately 3.7 kg lighter and when the one or two heaviest pigs in a pen were removed, d 28 post-marketing BW was approximately 4.8 kg lighter for pigs fed the 0.50%-Lys diet compared to pigs fed the control diet. There was no evidence of difference in ADFI.

From d 28 to 44, regardless of the previous diets fed from d 0 to 28, pigs fed the 0.18%-Lys diet had decreased ($P < 0.05$) ADG, G:F, Lys intake per day, and Lys intake per kg of gain compared to pigs fed the control or 0.50%-Lys diets (Table 4.2). Pigs fed the 0.50%-Lys diet for 44-d had decreased ($P < 0.05$) ADG, G:F, Lys intake per day, and Lys intake per kg of gain compared to pigs fed the control diet for the entire 44-d study.

For the overall period (d 0–44), there was no evidence of difference in ADFI between treatments (Table 4.2). Pigs fed the 0.50%-Lys diet (d 0–28) then the 0.18%-Lys diet (d 28–44) had decreased ($P < 0.05$) ADG, G:F, final BW, and Lys intake per day compared to the three other treatments, and were approximately 11.8 kg lighter than pigs fed the control diet (Figure 4.3). There was no evidence of difference between pigs fed the 0.50%-Lys diet for 44-d and pigs fed the control diet (d 0–28) then the 0.18%-Lys diet (d 28–44) in ADG, G:F, and final BW. Pigs

on these two treatments had decreased ($P < 0.05$) ADG and G:F, and final BW (~7 kg lighter), compared to pigs fed the control diet for 44-d. All pigs fed the 0.50%-Lys diet from d 0 to 28 had decreased ($P < 0.05$) overall Lys intake per kg of gain compared to pigs fed the control diet from d 0 to 28. There were no differences in removals, mortality, or incidences of tail-biting or other vices (data not shown). Overall, pig health was very good throughout the study.

For carcass characteristics, there was no evidence of difference in carcass yield between treatments (Table 4.2). Pigs fed the 0.50%-Lys diet (d 0–28) then the 0.18%-Lys diet (d 28–44) had decreased ($P < 0.05$) HCW, percentage lean, loin depth, and increased ($P < 0.05$) backfat depth compared to pigs fed the control diet for 44-d. There was no evidence of a difference in backfat depth, loin depth, and percentage lean between the pigs fed the 0.50%-Lys for 44 days, the pigs fed the control diet (d 0–28) then the 0.18%-Lys diet (d 28–44), and the pigs fed the 0.50%-Lys diet (d 0–28) then 0.18%-Lys diet (d 28–44).

Revenue per pig was calculated using either the low market value at the time of the study ($0.66/ kg; low) or a more typical market value ($1.43/kg; standard; Table 4.3). Pigs fed the 0.50%-Lys diet (d 0–28) then the 0.18%-Lys diet (d 28–44) had decreased ($P < 0.05$) revenue, using either the low or standard pricing model, compared to all other treatments, and had increased ($P < 0.05$) feed cost per kg of gain and decreased IOFC (low pricing) compared to pigs fed the control or the 0.50%-Lys treatments for 44 d. Pigs fed the 0.18%-Lys diets from d 28 to 44 had decreased ($P < 0.05$) IOFC (low and standard pricing) per pig placed and feed cost compared to pigs fed the control diet for 44-d. There was no evidence of a difference in all economic criteria between pigs fed the control diet (d 0–28) then 0.18%-Lys diet (d 28–44) and pigs fed the 0.50%-Lys diet for 44 d.

Experiment 2

From d 0 to 14, pigs fed the 0.18%-Lys diet had decreased ($P < 0.05$) ADG, ADFI, G:F, d 14 BW, and Lys intake per day compared to pigs fed the control diet (Table 4.4). Day 14 BW was approximately 8 kg lighter for pigs fed the 0.18%-Lys diet compared to pigs of the control group (Figure 4.4). There was no evidence of a difference in Lys intake per kg of gain.

From d 14 to 21, pigs previously fed the 0.18%- Lys diet for 14-d and then switched to the control diet exhibited compensatory gain with increased ($P < 0.05$) ADG, ADFI, G:F Lys intake per day, and improved ($P < 0.05$) Lys intake per kg of gain, but still lower ($P < 0.05$) d 21 BW compared to pigs in the control group. Pigs that remained on the 0.18%-Lys diet had decreased ($P < 0.05$) d 21 BW, Lys intake per day, and improved ($P < 0.05$) Lys intake per kg of gain compared to all other treatments. They also had decreased ($P < 0.05$) ADG compared to the pigs previously fed the 0.18%-Lys diet and switched to the control diet. There was no evidence of a difference in ADFI and G:F between pigs in the control group and pigs fed the 0.18%- Lys diet for 21-d.

From d 21 to 28, pigs previously fed the 0.18%- Lys diet for 21-d and then switched to the control diet had compensatory gain with increased ($P < 0.05$) ADG and ADFI. However, d 28 BW was decreased ($P < 0.05$) compared to pigs in the control group. Pigs fed the 0.18%-Lys diet for 21-d before being switched to the control diet also had decreased ($P < 0.05$) d 28 BW compared to pigs fed the 0.18%- Lys diet for the first 14-d before being switched to the control diet thereafter. Pigs fed the 0.18%-Lys diet for 14 of the 44-d continued to have decreased ($P < 0.05$) d 28 BW compared to pigs in the control group. Pigs fed the 0.18%-Lys diet for 28-d had decreased ($P < 0.05$) ADG, G:F, d 28 BW, and Lys intake per day, and improved ($P < 0.05$) Lys intake per kg of gain compared to all other treatments.

On d 44, pigs fed the 0.18%-Lys diet for 28-d had been switched to and provided the control diet for the final 16-d, pigs fed the 0.18%-Lys diet for 21-d had been provided with the control diet for 23-d, and pigs fed the 0.18%-Lys diet for 14-d had been provided with the control diet for 30-d. From d 28 to 44, ADG, G:F, and Lys intake per kg of gain improved (linear, $P < 0.001$) as time since switching to the control diet increased. Average daily feed intake and Lys intake per day tended to increase (linear, $P = 0.053$) as time since switching to the control diet increased. All treatments which were provided with the 0.18%-Lys diet demonstrated compensatory growth following the transition to the control diet at the respective time points, and the rate of improvement in growth performance by compensatory growth was reduced over time.

For the overall period (d 0–44), there was no evidence of a difference in ADFI between all treatments (Table 4.4). Average daily gain and Lys intake per kg of gain decreased (linear, $P < 0.001$), and G:F and Lys intake per day decreased (quadratic, $P < 0.028$) as the duration of Lys restriction increased. There were no differences in removals, mortality, or incidences of tail-biting or other vices (data not shown). Overall, pig health was very good throughout the study.

For carcass characteristics, HCW, carcass yield, loin depth, and percentage lean decreased (linear, $P \leq 0.007$) as the duration of Lys restriction increased (Table 4.4). Backfat depth increased (linear, $P < 0.001$) as the duration of Lys restriction increased.

Revenue (standard and low), feed cost, and IOFC (standard and low) were decreased (linear, $P < 0.001$) as the duration of Lys restriction increased (Table 4.5). Feed cost per kg of gain was increased (linear, $P < 0.001$; quadratic, $P = 0.018$) as the duration of Lys restriction increased.

Discussion

The 2020 COVID-19 pandemic caused an abnormal market scenario where the US pork industry had a substantial reduction in the ability to process market pigs due to packing plant closures. The reduced processing capacity resulted in a longer growth period which led to the risk of pigs becoming too heavy for the infrastructure of the packing facility. Therefore, we conducted these two experiments to provide producers with a variety of strategies with Lys-deficient diets to reduce the growth rate of pigs and minimize economic hardship.

Dietary Standardized Ileal Digestible Lysine Requirement Estimates

The NRC (2012) SID Lys requirement estimate is 0.73% for 75- to 100-kg pigs and 0.61% for 100- to 135-kg pigs. Soto et al. (2019) reported that the predicted maximum ADG and G:F for pigs beyond 100-kg BW was achieved at 0.62% and 0.63% SID Lys, respectively. Distinct from regular Lys titration studies, we used diets (0.50%-Lys and 0.18%-Lys diet) that were severely deficient in Lys and other AAs for this weight range to evaluate the effects on growth performance. In both experiments, control pigs had greater Lys intake per day and ADG compared to pigs fed Lys-restricted diets. On average, control pigs consumed approximately 18–20 g/d SID Lys where pigs fed 0.18% SID Lys diets consumed approximately 10–12 g/d. Similarly, Soto et al. (2019) reported a decrease in ADG and G:F as SID Lys intake per day decreased in 100- to 135-kg pigs, but the magnitude of reduction was less than what we observed in our experiments with severely deficient Lys diets. Goncalves et al. (2017) reported that the optimal performance for ADG and G:F of 100- to 135-kg pigs was associated with a SID Lys intake per day of 19.5 and 19.7 g/d, respectively. Whereas the NRC (2012) requirement estimate for SID Lys is 16.9 g/d for this same weight range.

In response to COVID 19 induced abnormal marketing situations, Helm et al. (2021) observed that late-finishing pigs fed a diet containing 97% corn (0.16% SID Lys) had decreased ADG, G:F, and increased ($P < 0.05$) backfat depth compared to pigs fed a control diet. Our findings are consistent with Helm et al. (2021) in that severe Lys restriction will dramatically decrease growth performance and carcass leanness. In both of our experiments, pigs restricted in Lys and other AAs had increased backfat depth and decreased percentage lean compared to the nonrestricted pigs.

Compensatory Growth

Compensatory growth has been categorized into complete, incomplete, and no compensatory growth (Menegat et al., 2020). It can be affected by several factors, such as the stage of growth at restriction, severity of restriction, and duration of restriction and recover periods (Skiba, 2005; Hector and Nakagawa, 2012; Menegat et al., 2020). Complete compensatory growth refers to previously restricted pigs having faster growth rates during recovery and obtaining a similar BW compared to nonrestricted pigs at a similar age. Incomplete compensatory growth refers to previously restricted pigs having faster growth rates during recovery, but the magnitude of improvement is not enough to obtain a similar BW compared to nonrestricted pigs at a similar age. No compensatory growth refers to previously restricted pigs having similar or reduced growth rates during recovery compared to nonrestricted pigs. According to Menegat et al. (2020), compensatory growth seems to happen if: 1) Lys restriction is between 10% and 30%; 2) Lys restriction is induced before pigs reach maximum protein deposition; 3) duration of Lys restriction is short (<45% of overall period) and duration of recovery is long (>55% of overall period); and 4) Lys concentration during recovery needs to be close to or above the estimated requirements. In our study, all restricted pigs showed

compensatory growth, especially during the first week of recovery. The compensatory growth would be characterized as incomplete compensatory growth, because the restricted pigs did not reach a similar d 44 BW as the non-restricted pigs (Figure 4.4). However, the magnitude of compensatory growth was greater as the period of restriction was shorter and the period of recovery was greater. Restricted pigs had increasing backfat depth and decreasing lean percentage as the duration of restriction increased, indicating that restricted pigs had greater fat deposition and lower lean deposition compared to the control pigs.

The average difference in growth rate between pigs fed the control diet and pigs fed the 0.18%-Lys diet was about 49%, which resulted in the reduced BW during restriction. During the recovery period, previously restricted pigs grew faster than control pigs with a greater improvement in ADG during the first week (28% increase) compared to subsequent weeks (12% increase; Figure 4.5). Using these rates of recovery, for the restricted pigs to achieve similar BW as the control, pigs restricted for 14 d would require 34 d of recovery, pigs restricted for 21 d would require 55 d of recovery, and pigs restricted for 28 d would require 75 d of recovery.

Physiological changes that can explain the compensatory growth during the recovery are observed throughout the literature. For Lys restricted grow-finish pigs, the main driver for compensatory growth is an improvement in G:F because ADFI does not appear to change (Menegat et al., 2020). The improved G:F can be explained by the improvement in nitrogen utilization, Lys efficiency, protein deposition, and lean growth in the restricted pigs for reaching target body composition as the nonrestricted pigs at a similar age (Menegat et al., 2020). Sun et al. (2020) observed that liver metabolic function and small intestinal absorptive function of the restricted pigs were increased during a recovery period. Insulin-like growth factor (IGF), IGF-binding protein, cortisol, and corticosterone, regulators of protein deposition, were also increased

during the recovery period (Martínez-Ramírez et al., 2009; Ishida et al., 2012). These changes in hormone status suggest an improvement in protein deposition and growth rate. Therefore, these improvements may contribute to the improved G:F of the restricted pigs in our study. In Exp. 2, d 0–14 ADFI was lower for pigs fed 0.18%-Lys diet compared with the control pigs (Figure 4.6). However, we observed greater ADFI during the recovery period, especially the first week. The decreased ADFI might be the result of an AA imbalance, then ADFI increased when pigs were switched to an AA balanced control diet.

Economic Significance of Reducing Growth Rate

Even though Lys-restricted diets are lower cost, feeding late-finishing pig diets with sub-optimal Lys concentrations would not be economical because of the reduced grow rate and poor feed efficiency. However, under abnormal market scenarios when processing plants lack capacity to keep up with the number of pigs produced, these pigs will need to stay at the farm for an extended period and may grow to weights beyond the maximum market weight feasible for processing plants. Pigs marketed greater than the packer's preferred weight range are often severely discounted in price. If excessive weight gain becomes a detriment, such as the situation with COVID-19 shutting down processing plants, feeding Lys restricted diets will reduce ADG resulting in more acceptable BWs, which would increase the chances that the pigs could generate more income in this abnormal scenario. These nutritional strategies provide an estimate of growth rate for producers to have a more flexible timeline to manage the BW of their finishing pigs based on the availability of the processing plants. This in turn has the potential to minimize the economic loss of these pigs.

In conclusion, using nutritional strategies to reduce growth rates of finishing pigs allows producers to cope with the dynamic changes in processing plant capacity to minimize economic

losses during abnormal market scenarios. Moreover, compensatory growth can be observed in Lys-restricted late-finishing pigs, but the duration of restriction and recovery periods are crucial factors influencing the magnitude of compensatory growth.

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Table 4.1. Composition of experimental diets (as-fed basis)

Items	Control	0.50%-Lys	0.18%-Lys[3]
Ingredients, %			
Corn	86.41	92.99	98.22
Soybean meal	11.53	5.00	--
Limestone, ground	0.89	0.88	0.86
Monocalcium phosphate	0.26	0.36	0.43
Salt	0.35	0.35	0.35
L-Lysine-HCl	0.30	0.25	--
Methionine hydroxy analog, dry	0.01	--	--
L-Threonine	0.09	0.03	--
L-Tryptophan	0.02	0.01	--
Vitamin and trace mineral premixes[1]	0.16	0.16	0.16
Total	100	100	100
Calculated analysis			
Standardized ileal digestible (SID) amino acids, %			
Lysine	0.70	0.50	0.18
Isoleucine:lysine	60	62	124
Leucine:lysine	156	187	452
Methionine:lysine	30	34	81
Methionine and cysteine:lysine	58	68	163
Threonine:lysine	65	61	117
Tryptophan:lysine	18.6	15.9	25.9
Valine:lysine	70	77	168
Lysine:net energy, g/Mcal	2.73	1.93	0.69
Net energy, kcal/kg	2,564	2,599	2,623
Crude protein, %	13.0	10.3	8.1
Ca, %	0.47	0.46	0.45
STTD P,[2] %	0.24	0.24	0.24
Chemical analysis,[3] %			
Dry matter	88.7	88.7	88.9
Crude protein	12.6	10.2	8.1

[1]Provided per kg of diet: 1,240.10 IU vitamin A; 496.04 IU vitamin D; 13.23 IU vitamin E; 0.99 mg vitamin K; 0.01 mg vitamin B12; 14.88 mg niacin; 8.27 mg pantothenic acid; 2.48 mg riboflavin; 55 mg Zn from zinc sulfate; 55 mg Fe from iron sulfate; 17 mg Mn from manganese oxide; 8 mg Cu from copper sulfate; 0.15 mg I from calcium iodate; 0.15 mg Se from sodium selenite; and 375 FTU Ronozyme HiPhos GT 2700 (DSM Nutritional Products, Basel, Switzerland) with an expected STTD P release of 0.08%.

[2]STTD P = standardized total tract digestible phosphorus.

[3]A representative sample of each diet was collected from the feeders of each treatment, homogenized, and analyzed (Ward Laboratories, Inc., Kearney, NE).

Table 4.2. Effect of nutritional strategies to reduce growth rate of pigs beyond 90-kg body weight, Exp. 1[1,2].

d 0 to 28	Control[3]		0.50%-Lys		
d 28 to 44	Control	0.18%-Lys	0.50%-Lys	0.18%-Lys	Probability[4], *P* <
d 0 to 28					
ADG, kg	0.84 ± 0.016		0.71 ± 0.009		< 0.001
ADFI, kg	2.77 ± 0.028		2.78 ± 0.028		0.832
G:F	0.301 ± 0.004		0.254 ± 0.002		< 0.001
Lys intake, g/d	19.4 ± 0.21		13.9 ± 0.15		< 0.001
Lys intake, g/kg gain	23.3 ± 0.28		19.7 ± 0.14		< 0.001
d 0 BW, kg	89.1 ± 1.10		89.0 ± 1.10		0.708
d 28 BW, kg (pre-marketing)[5]	112.5 ± 1.22		108.8 ± 1.13		< 0.001
d 28 to 44					
ADG, kg	0.86 ± 0.032^{a}	0.48 ± 0.032^{c}	0.71 ± 0.032^{b}	0.44 ± 0.032^{c}	< 0.001
ADFI, kg	2.60 ± 0.058^{a}	2.42 ± 0.058^{ab}	2.46 ± 0.058^{ab}	2.26 ± 0.058^{b}	0.005
G:F	0.331 ± 0.0150^{a}	0.197 ± 0.0100^{b}	0.289 ± 0.0066^{a}	0.195 ± 0.0065^{b}	< 0.001
Lys intake, g/d	18.2 ± 0.42^{a}	4.4 ± 0.12^{c}	12.3 ± 0.29^{b}	4.1 ± 0.09^{c}	< 0.001
Lys intake, g/kg gain	21.6 ± 1.16^{a}	9.5 ± 0.56^{c}	17.4 ± 0.44^{b}	9.4 ± 0.31^{c}	< 0.001
d 28 BW, kg (post-marketing)[5]	111.2 ± 1.41^{a}	111.2 ± 1.41^{a}	106.4 ± 1.41^{b}	106.5 ± 1.41^{b}	< 0.001
d 44 BW, kg	125.3 ± 1.47^{a}	118.9 ± 1.98^{b}	117.8 ± 1.69^{b}	113.5 ± 1.25^{c}	< 0.001
d 0 to 44					
ADG, kg	0.86 ± 0.018^{a}	0.71 ± 0.018^{b}	0.72 ± 0.018^{b}	0.61 ± 0.018^{c}	< 0.001
ADFI, kg	2.72 ± 0.039	2.66 ± 0.039	2.69 ± 0.039	2.61 ± 0.039	0.221
G:F	0.315 ± 0.0042^{a}	0.268 ± 0.0042^{b}	0.267 ± 0.0042^{b}	0.235 ± 0.0042^{c}	< 0.001
Lys intake, g/d	19.0 ± 0.22^{a}	14.7 ± 0.22^{b}	13.5 ± 0.22^{c}	10.8 ± 0.22^{d}	< 0.001
Lys intake, g/kg gain	22.3 ± 0.33^{a}	20.7 ± 0.33^{b}	18.8 ± 0.33^{c}	17.6 ± 0.33^{c}	< 0.001
Carcass characteristics					
HCW, kg	93.5 ± 1.29^{a}	88.9 ± 1.24^{b}	87.5 ± 1.35^{bc}	84.5 ± 1.26^{c}	< 0.001

Carcass yield, %	74.8 ± 0.20	74.2 ± 0.19	74.2 ± 0.21	74.1 ± 0.20	0.096
Backfat depth, mm[6]	13.9 ± 0.34[b]	15.2 ± 0.30[a]	15.3 ± 0.34[a]	15.8 ± 0.32[a]	0.002
Loin depth, mm[6]	62.0 ± 0.60[a]	59.1 ± 0.53[b]	59.8 ± 0.60[ab]	58.1 ± 0.56[b]	< 0.001
Lean, %[5]	55.5 ± 0.20[a]	54.5 ± 0.18[b]	54.6 ± 0.20[b]	54.0 ± 0.19[b]	< 0.001

[a,b,c,d] Means within a row with different superscripts differ ($P < 0.05$).

[1]A total of 356 pigs (initially 89 kg) were used with 10 pigs per pen and 9 replicates per treatment. On d 28, one or two heaviest pigs in each pen were selected and marketed as standard farm marketing protocol. These heavy pigs were included in the d 0 to 28 growth performance data and d 28 pre-marketing BW, but not in d 28 post-marketing BW and carcass data.

[2]BW = body weight. ADG = average daily gain. ADFI = average daily feed intake. G:F = feed efficiency. HCW = hot carcass weight

[3]SID lysine (%) was 0.70 for the control diet, 0.50 for the 0.50%-Lys diet, and 0.18 for the 0.18%-Lys diet.

[4]Treatment *F*-test based on ANOVA.

[5]On d 28, one or two of the heaviest pigs in each pen were selected and marketed resulting in 8 remaining pigs per pen for all pens until d 44. These pigs were included in the d 0 to 28 growth performance data but not carcass data.

[6]Adjusted using HCW as covariate.

Table 4.3. Effect of nutritional strategies to reduce growth rate of pigs beyond 90-kg body weight, Exp. 1[1]

d 0 to 28	Control[2]		0.50%-Lys		
d 28 to 44	Control	0.18%-Lys	0.50%-Lys	0.18%-Lys	Probability[3], $P <$
Economics (per pig placed), $[4]					
Revenue (low)[5]	17.28 ± 0.355[a]	14.26 ± 0.355[b]	14.41 ± 0.355[b]	12.30 ± 0.355[c]	< 0.001
Revenue (standard)[6]	37.44 ± 0.769[a]	30.90 ± 0.769[b]	31.23 ± 0.769[b]	26.65 ± 0.769[c]	< 0.001
Feed cost[7]	18.59 ± 0.257[a]	17.24 ± 0.257[b]	16.62 ± 0.257[bc]	15.68 ± 0.257[c]	< 0.001
Feed cost per kg of gain[8]	0.53 ± 0.009[c]	0.59 ± 0.009[ab]	0.57 ± 0.009[bc]	0.63 ± 0.009[a]	< 0.001
IOFC (low)[9]	-1.32 ± 0.232[a]	-2.98 ± 0.232[bc]	-2.21 ± 0.232[b]	-3.38 ± 0.232[c]	< 0.001
IOFC (standard)	18.84 ± 0.598[a]	13.66 ± 0.598[b]	14.61 ± 0.598[b]	10.97 ± 0.598[c]	< 0.001

[a,b,c] Means within a row with different superscripts differ ($P < 0.05$).

[1] A total of 356 pigs (initially 89 kg) were used with 10 pigs per pen and 9 replicates per treatment.

[2]SID lysine (%) was 0.70 for the control diet, 0.50 for the 0.50%-Lys diet, and 0.18 for the 0.18%-Lys diet.

[3]Treatment *F*-test based on ANOVA.

[4]Removal rates were similar between all treatments.

[5]Revenue (low) = \$0.66 × (total live weight gain × carcass yield).

[6]Revenue (standard) = \$1.43 × (total live weight gain × carcass yield).

[7]Feed cost per kg: \$0.17 (control diet); \$0.15 (0.50%-Lys diet); and \$0.14 (0.18%-Lys diet).

[8]Feed cost per kg gain = (total pen feed cost) / (total pen gain).

[9]IOFC (income over feed cost) = revenue – feed cost.

Table 4.4. Evaluation of compensatory growth of 90-kg finishing pigs previously fed a reduced Lys diet, Exp. 2 [1,2,3].

d 0 to 14	Control	0.18%-Lys					
d 14 to 21	Control	Control	0.18%-Lys				
d 21 to 28	Control	Control	Control	0.18%-Lys	Probability, *P* <		
d 28 to 44	Control	Control	Control	Control	Treatment[4]	Linear[5]	Quadratic[5]
d 0 to 14							
d 0 BW, kg	88.6 ± 1.05		88.6 ± 0.94		0.963	--	--
d 14 BW, kg	99.7 ± 1.00[a]		91.8 ± 0.93[b]		< 0.001	--	--
ADG, kg	0.79 ± 0.025[a]		0.23 ± 0.015[b]		< 0.001	--	--
ADFI, kg	2.48 ± 0.048[a]		2.18 ± 0.029[b]		< 0.001	--	--
G:F	0.317 ± 0.0093[a]		0.103 ± 0.0054[b]		< 0.001	--	--
Lys intake, g/d	17.4 ± 0.29[a]		4.0 ± 0.05[b]		< 0.001	--	--
Lys intake, g/kg gain	22.2 ± 0.57		19.6 ± 1.54		0.121	--	--
d 14 to 21							
d 21 BW, kg	106.0 ± 1.00[a]	101.1 ± 1.00[b]	97.2 ± 0.93[c]		< 0.001	--	--
ADG, kg	0.89 ± 0.050[b]	1.34 ± 0.050[a]	0.76 ± 0.036[b]		< 0.001	--	--
ADFI, kg	2.63 ± 0.076[b]	3.01 ± 0.076[a]	2.73 ± 0.054[b]		< 0.001	--	--
G:F	0.336 ± 0.0179[b]	0.446 ± 0.0179[a]	0.280 ± 0.0137[c]		< 0.001	--	--
Lys intake, g/d	18.4 ± 0.45[b]	21.1 ± 0.39[a]	5.0 ± 0.11[c]		< 0.001	--	--
Lys intake, g/kg gain	21.6 ± 1.52[a]	15.8 ± 0.42[b]	6.8 ± 0.38[c]		< 0.001	--	--
d 21 to 28							
d 28 BW, kg	112.7 ± 1.05[a]	108.7 ± 1.05[b]	105.7 ± 1.05[c]	101.2 ± 1.05[d]	< 0.001	--	--
ADG, kg	0.95 ± 0.062[b]	1.09 ± 0.062[ab]	1.23 ± 0.062[a]	0.56 ± 0.062[c]	< 0.001	--	--
ADFI, kg	2.59 ± 0.091[b]	2.87 ± 0.091[ab]	2.98 ± 0.091[a]	2.78 ± 0.091[ab]	0.040	--	--
G:F	0.365 ± 0.0152[a]	0.378 ± 0.0152[a]	0.412 ± 0.0152[a]	0.201 ± 0.0152[b]	< 0.001	--	--
Lys intake, g/d	18.2 ± 0.88[a]	20.1 ± 0.51[a]	20.9 ± 0.58[a]	5.1 ± 0.13[b]	< 0.001	--	--
Lys intake, g/kg gain	19.4 ± 0.82[a]	18.6 ± 0.82[a]	17.2 ± 0.82[a]	9.9 ± 0.82[b]	< 0.001	--	--

d 28 to 44							
d 44 BW, kg	126.0 ± 1.12	123.9 ± 1.12	120.8 ± 1.12	118.5 ± 1.12	< 0.001	< 0.001	0.123
ADG, kg	0.83 ± 0.021	0.94 ± 0.021	0.94 ± 0.021	1.06 ± 0.021	< 0.001	< 0.001	0.200
ADFI, kg	2.67 ± 0.122	2.80 ± 0.122	2.75 ± 0.122	2.85 ± 0.122	0.168	0.053	0.904
G:F	0.311 ± 0.0053	0.336 ± 0.0053	0.342 ± 0.0053	0.374 ± 0.0053	< 0.001	< 0.001	0.083
Lys intake, g/d	18.7 ± 0.386	19.6 ± 0.386	19.2 ± 0.386	19.9 ± 0.386	0.168	0.053	0.904
Lys intake, g/kg gain	22.6 ± 0.331	20.9 ± 0.331	20.5 ± 0.331	18.7 ± 0.331	< 0.001	< 0.001	0.227
d 0 to 44							
ADG, kg	0.85 ± 0.018	0.80 ± 0.018	0.73 ± 0.018	0.67 ± 0.018	< 0.001	< 0.001	0.111
ADFI, kg	2.59 ± 0.041	2.65 ± 0.041	2.59 ± 0.041	2.61 ± 0.041	0.717	0.858	0.544
G:F	0.325 ± 0.040	0.301 ± 0.040	0.280 ± 0.040	0.257 ± 0.040	< 0.001	< 0.001	0.028
Lys intake, g/d	18.1 ± 0.238	14.9 ± 0.238	12.3 ± 0.238	10.1 ± 0.238	< 0.001	< 0.001	0.024
Lys intake, g/kg gain	21.6 ± 0.36	18.7 ± 0.18	17.0 ± 0.18	15.0 ± 0.12	< 0.001	< 0.001	0.097
Carcass characteristics							
HCW, kg	94.3 ± 1.55	92.4 ± 1.19	91.0 ±1.35	87.8 ± 1.38	0.017	0.004	0.292
Carcass yield, %	74.7 ± 0.26	73.8 ± 0.21	74.3 ± 0.23	73.5 ± 0.23	0.003	0.003	0.913
Backfat depth, mm	14.5 ± 0.24	15.2 ± 0.24	15.5 ± 0.24	15.8 ± 0.24	0.007	< 0.001	0.919
Loin depth, mm	62.8 ± 0.58	60.7 ± 0.57	58.6 ± 0.59	57.6 ± 0.58	< 0.001	< 0.001	0.651
Lean, %	54.9 ± 0.24	54.5 ± 0.18	54.1 ± 0.20	54.0 ± 0.21	0.048	0.007	0.792

[a,b,c,d] Means within a row with different superscripts differ ($P \leq 0.05$).

[1]A total of 346 pigs (initially 88.6 kg) were used with 9 to 10 pigs per pen and 9 replicates per treatment.

[2]BW = body weight. ADG = average daily gain. ADFI = average daily feed intake. G:F = feed efficiency. HCW = hot carcass weight

[3]SID lysine (%) was 0.70 for the control diet and 0.18 for the 0.18%-Lys diet.

[4]Treatment *F*-test based on ANOVA.

[5]Polynomial contrasts were constructed to evaluate the effects of duration of feeding pigs the 0.18%-Lys diet for d 28 to 44 and overall period.

Table 4.5. Evaluation of compensatory growth of 90-kg finishing pigs previously fed a reduced Lys diet, Exp. 2[1].

d 0 to 14	Control	0.18%-Lys					
d 14 to 21	Control	Control	0.18%-Lys				
d 21 to 28	Control	Control	Control	0.18%-Lys	Probability, $P <$		
d 28 to 44	Control	Control	Control	Control	Treatment[2]	Linear[3]	Quadratic[3]
Economics (per pig placed), $[4]							
Revenue (low)[5]	18.12 ± 0.433	17.02 ± 0.433	15.52 ± 0.433	14.31 ± 0.433	< 0.001	< 0.001	0.182
Revenue (standard)[6]	39.27 ± 0.937	36.87 ± 0.937	33.62 ± 0.937	31.01 ± 0.937	< 0.001	< 0.001	0.182
Feed cost[7]	18.91 ± 0.343	18.44 ± 0.343	17.36 ± 0.343	17.08 ± 0.343	0.002	< 0.001	0.501
Feed cost per kg of gain[8]	0.516 ± 0.0062	0.529 ± 0.0062	0.551 ± 0.0062	0.579 ± 0.0062	< 0.001	< 0.001	0.018
IOFC (low)	-0.78 ± 0.191	-1.43 ± 0.191	-1.84 ± 0.191	-2.76 ± 0.191	< 0.001	< 0.001	0.060
IOFC (standard)[9]	20.36 ± 0.929	18.42 ± 0.399	16.26 ± 0.696	13.94 ± 0.391	< 0.001	< 0.001	0.068

[1] A total of 346 pigs (initially 88.6 kg) were used with 9 to 10 pigs per pen and 9 replicates per treatment.
[2]Treatment *F*-test based on ANOVA.
[3]Polynomial contrasts were constructed to evaluate the effects of duration of feeding pigs the 0.18%-Lys diet for d 28 to 44 and overall period.
[4]Removal rates were similar between all treatments.
[5]Revenue (low) = $0.66 × (total live weight gain × carcass yield).
[6]Revenue (standard) = $1.43 × (total live weight gain × carcass yield).
[7]Feed cost per kg: $0.17 and $0.14 (0.18%-Lys diet).
[8]Feed cost per kg gain = (total pen feed cost) / (total pen gain).
[9]IOFC (Income over feed cost) = revenue – feed cost.

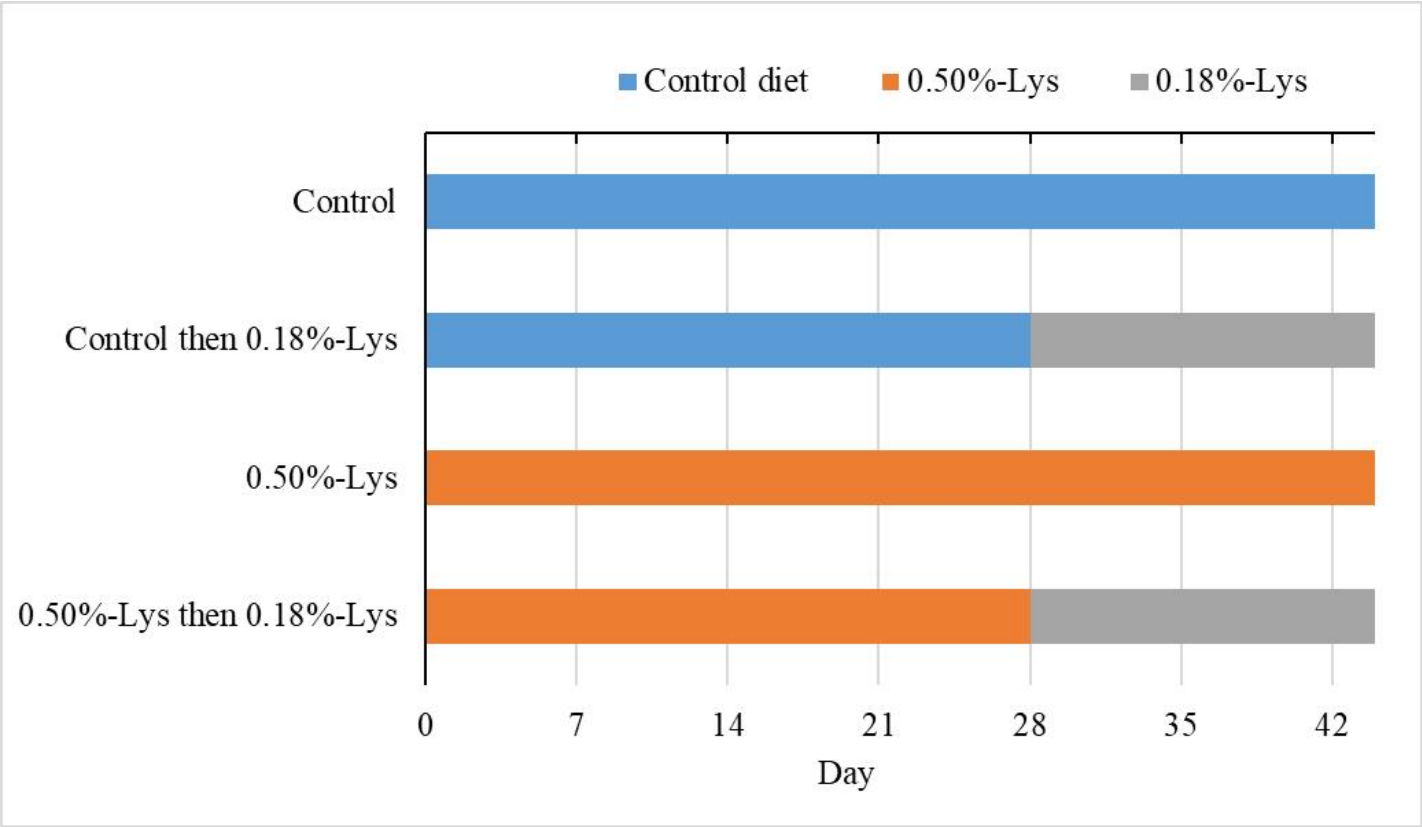

Figure 4.1. Experimental treatment design of Exp. 1.

A total of 3 diets were manufactured (control [0.70% SID Lys], 0.50%-Lys, and 0.18%-Lys). From d 0 to 28, pens received one of two dietary treatments (control or 0.50%-Lys). On d 28, pens previously fed the control diet were divided into two groups, half continued to be fed the control diet and the other half were fed to the 0.18%-Lys diet, which was fed until d 44. Pens previously fed the 0.50%-Lys diet were divided into two groups, half continued to be fed the 0.50%-Lys diet and the other half were fed the 0.18%-Lys diet, which was fed until d 44.

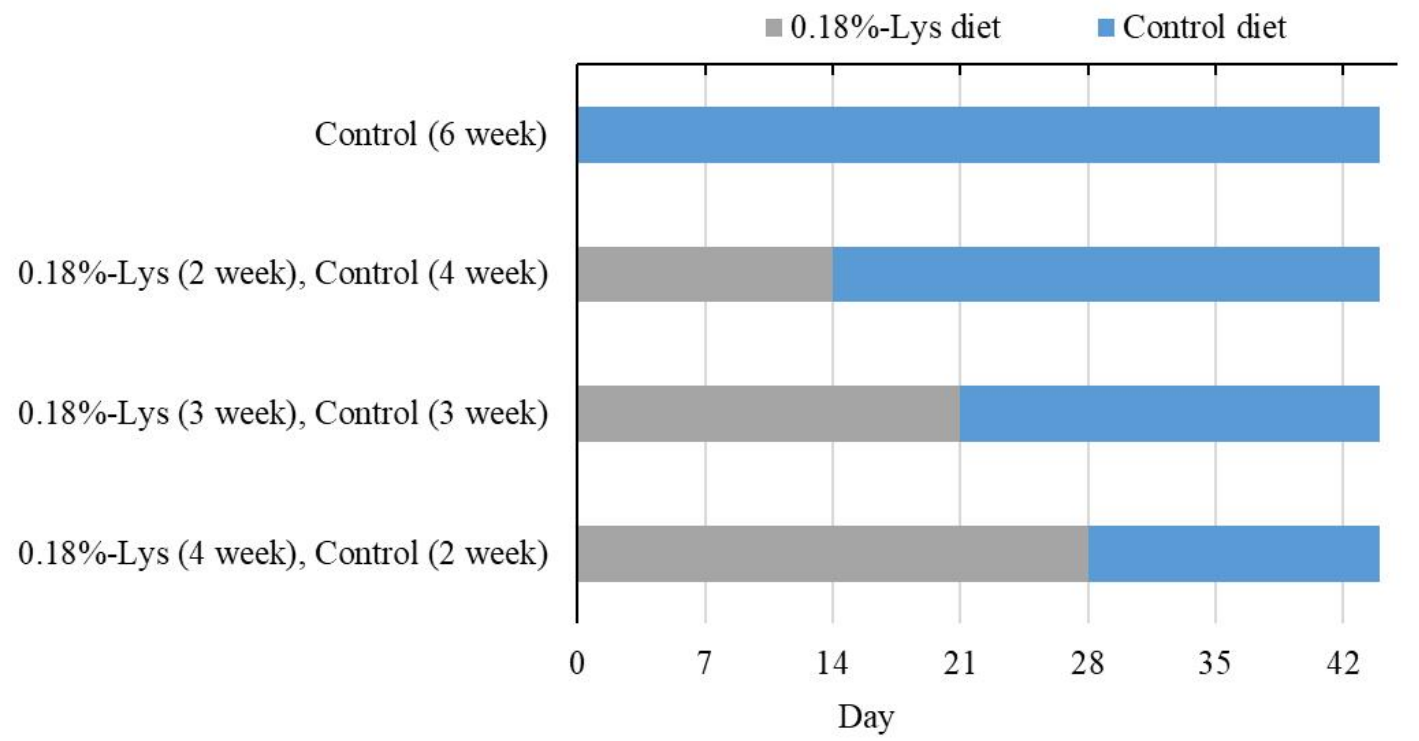

Figure 4.2. Experimental treatment design of Exp. 2.

A total of 2 diets were manufactured (control [0.70% SID Lys] and 0.18%-Lys). Nine pens of pigs were in the control group and fed the control diet from d 0 to 44. The other three treatments also consisted of 9 pens per treatment and were fed 0.18%-Lys diets for the first 14, 21, or 28-d and then fed the control diet until d 44.

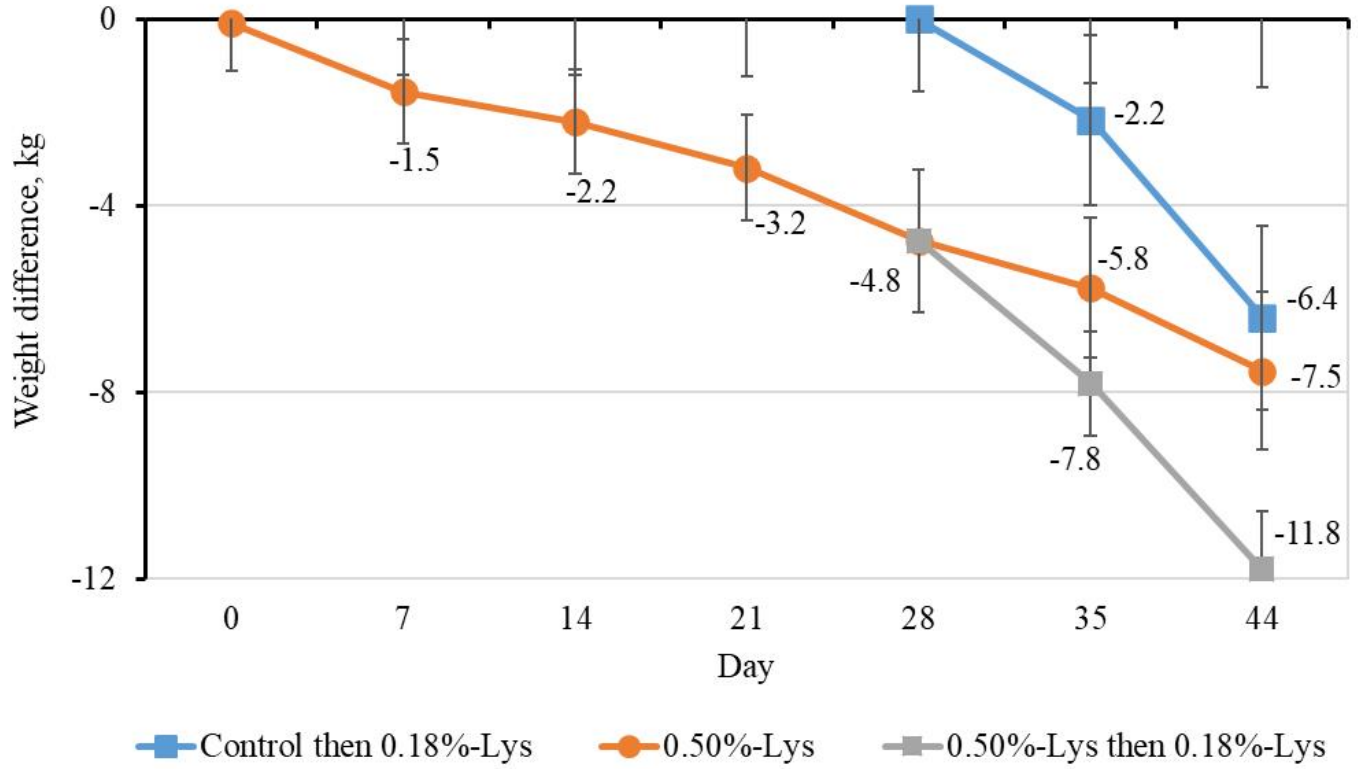

Figure 4.3. Exp. 1 body weight difference compared to control diet (horizontal axis at 0).

A total of 346 pigs (initially 89.0 kg) were used with 9–10 pigs per pen and 9 replicates per treatment. The weekly BW differences were calculated by subtracting the BW of pigs fed the control diet from BW of pigs fed other treatments. Two diets (control [0.70% SID Lys] and 0.50%-Lys) were fed to pigs from d 0 to 28. Four treatments were used from d 28 to 44. Error bar represents 1 SE.

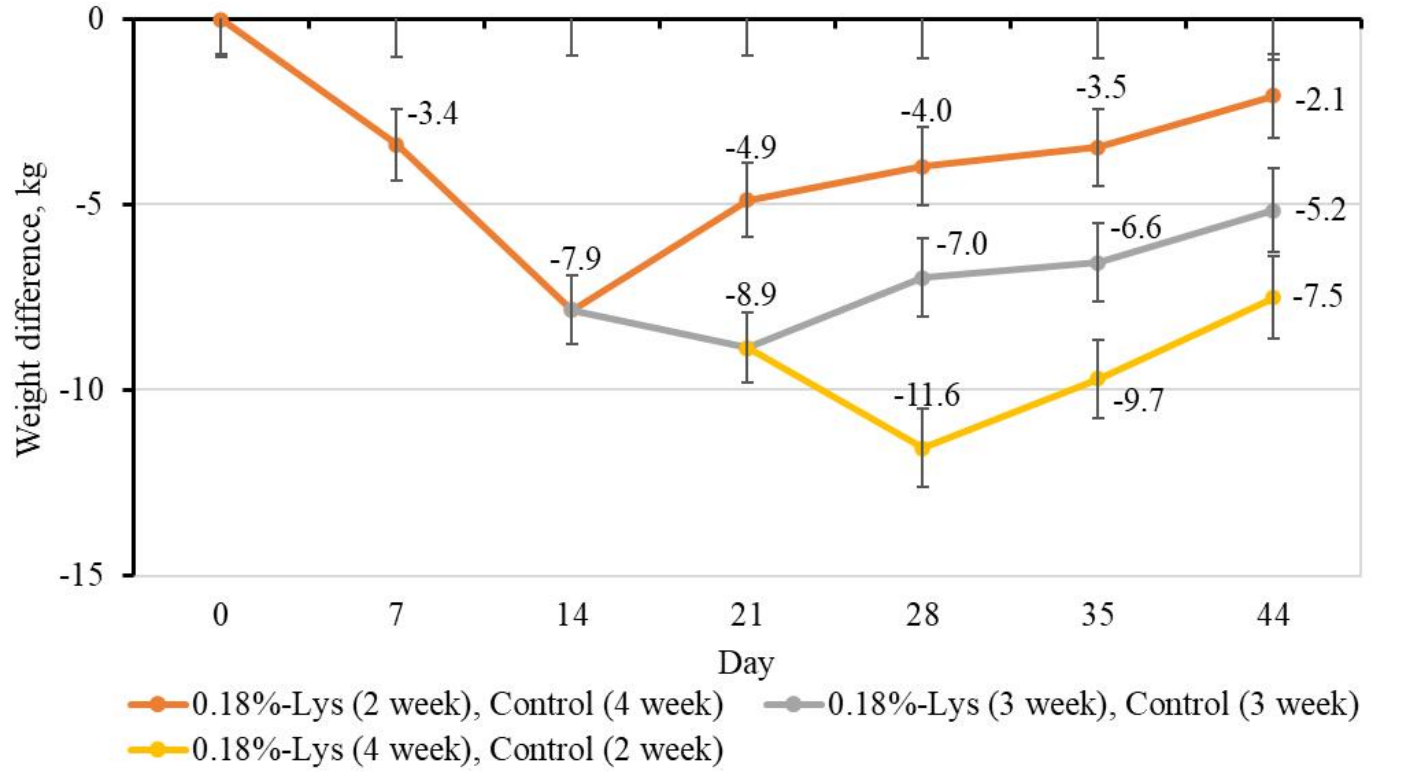

Figure 4.4. Exp. 2 body weight difference compared to control diet (horizontal axis at 0).

A total of 346 pigs (initially 88.6 kg) were used with 9–10 pigs per pen and 9 replicates per treatment. The weekly BW differences were calculated by subtracting the BW of pigs fed the control diet from BW of pigs fed other treatments. Error bar represents 1 SE.

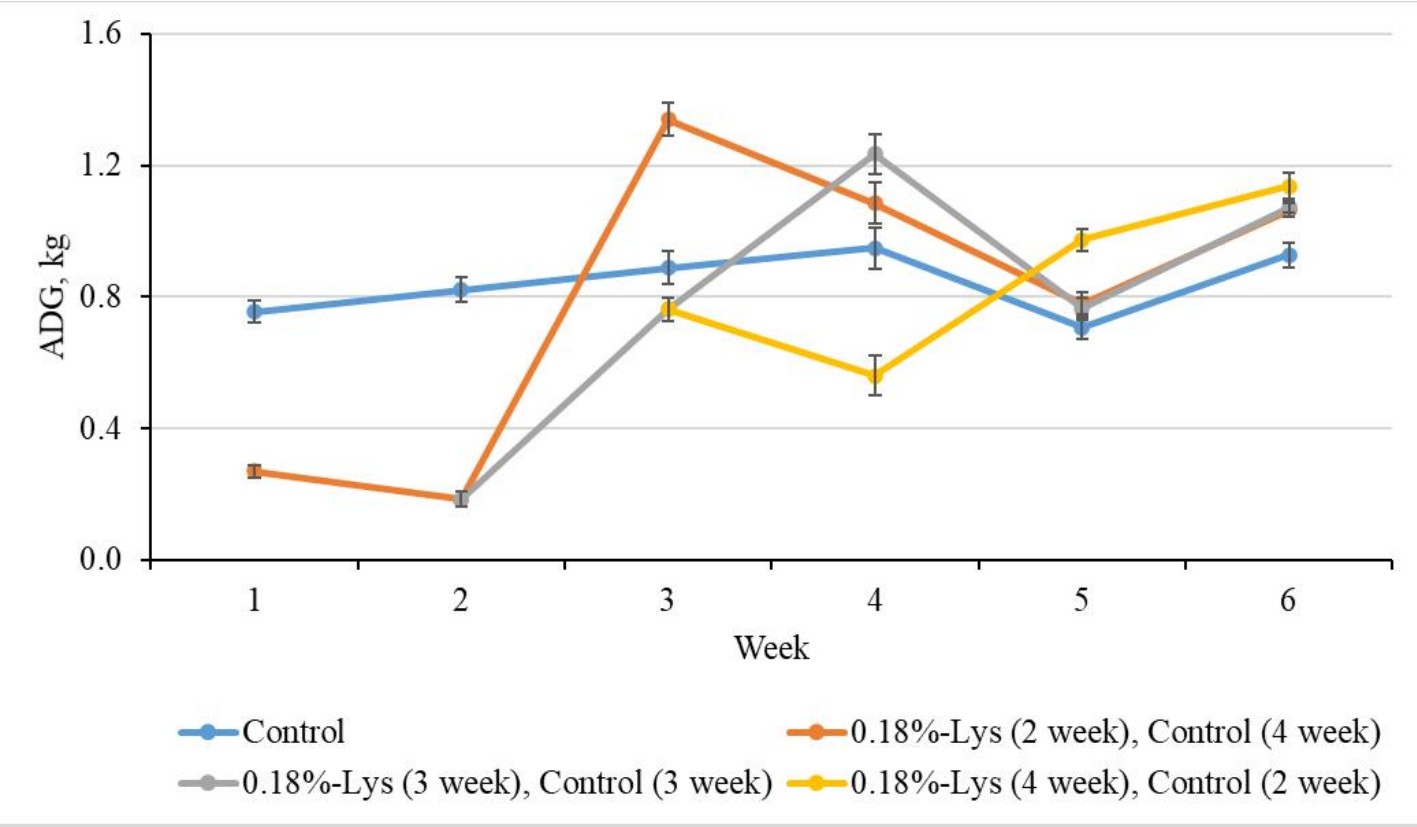

Figure 4.5. Exp. 2 weekly ADG of the 4 treatments.

A total of 346 pigs (initially 88.6 kg) were used with 9–10 pigs per pen and 9 replicates per treatment. Error bar represents 1 SE.

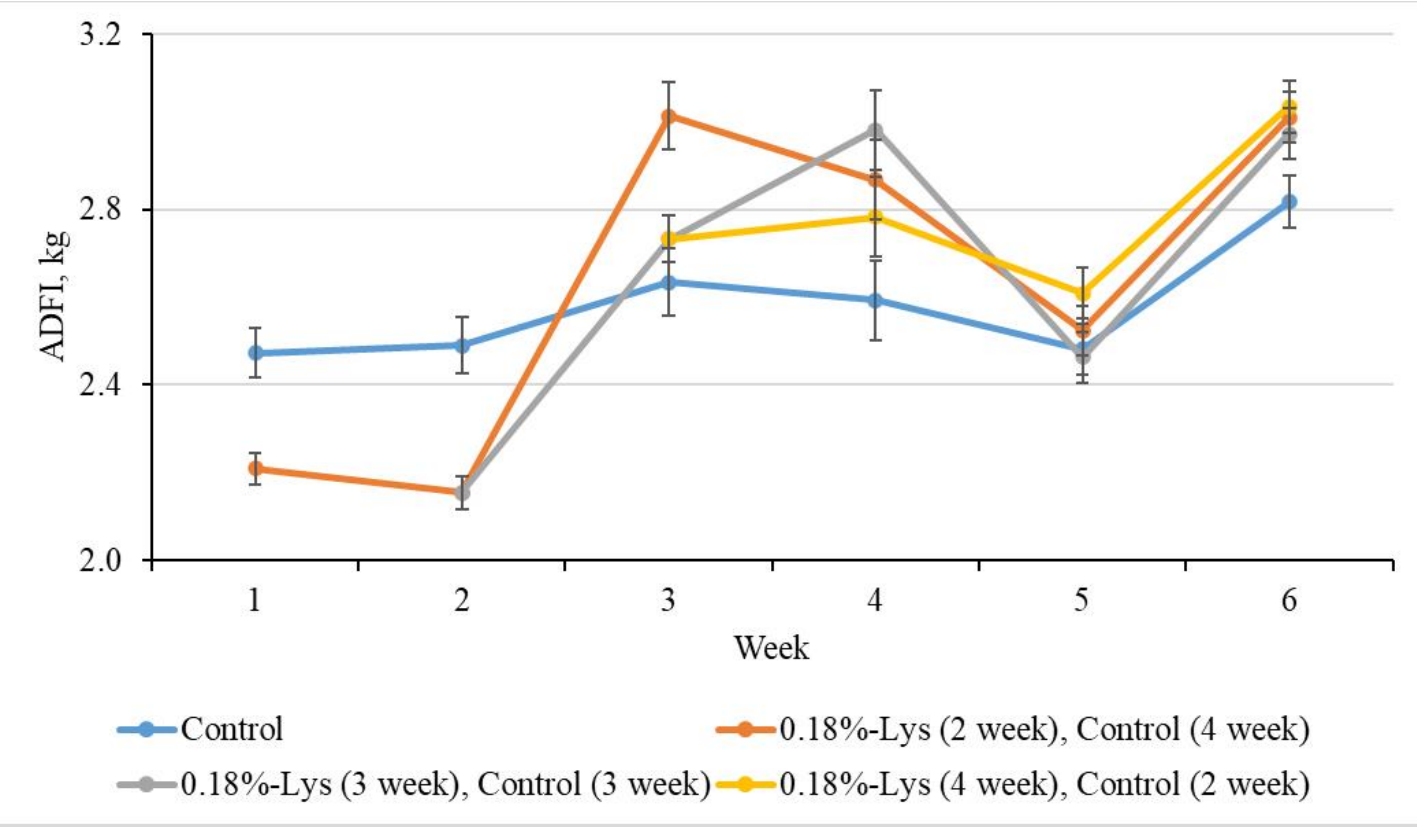

Figure 4.6. Exp. 2 weekly ADFI of the 4 treatments.

A total of 346 pigs (initially 88.6 kg) were used with 9–10 pigs per pen and 9 replicates per treatment. Error bar represents 1 SE.

Chapter 5 - Effect of different sow lactation feeder types and drip cooling on sow bodyweight, litter performance, and feeder cleaning criteria.

Abstract

A total of 600 sows (Line 3; PIC, Hendersonville, TN) were used to evaluate the effect of different lactation feeder types and drip cooling on sow farrowing performance and litter growth performance during the summer. For the feeder evaluation, the trial was conducted in 2 sequential groups with 300 sows per group. Five 60-farrowing-stall rooms with tunnel ventilation were used for each group. At approximately d 110 to 112 of gestation, sows were blocked by body condition score (BCS), parity, and offspring sire (Line 2 or Line 3 sires; PIC), then randomly allotted to 1 of 3 feeder types: 1) PVC tube feeder; 2) Rotecna feeder (Rotecna, Agramunt, Spain), or 3) SowMax feeder (Hog Slat, Newton Grove, NC). The 3 feeder types were placed in one of 3 stalls with the same sequence from the front to the end of all rooms to balance for environmental effects. For drip cooling evaluation, the trial was conducted during the 2nd group of 300 sows. Drippers were blocked in 3 of every 6 farrowing stalls to balance feeder type and environmental effects. After farrowing, sows had *ad libitum* access to feed. For litter performance data, only pigs from sows bred to Line 2 sires were recorded. Line 3 sire pigs were not included in litter performance data, but sows of these pigs were included in sow BW and feed disappearance data. After weaning, feeder cleaning time was recorded on a subsample of 67 feeders (19, 23, and 25 for PVC tube, Rotecna, and SowMax, respectively). There was no evidence of difference ($P > 0.05$) in sow entry BW, exit BW, BW change, and litter performance among the different feeder types. However, sows using the SowMax feeders had decreased ($P <$

0.05) total feed disappearance, average daily feed disappearance, and total feed cost compared to those fed with the PVC tube feeders. There was a marginal difference ($P < 0.10$) between feeder types in cleaning time, with PVC tube feeders requiring less time than the Rotecna feeders; however, cleaning time varied greatly between the personnel doing the cleaning. Sows with drip cooling had greater ($P < 0.05$) feed disappearance, litter growth performance, and subsequent total born, and reduced ($P < 0.05$) BW change. In conclusion, using a SowMax feeder reduced feed disappearance with no effects on sow and litter performance compared to a PVC tube feeder, and drip cooling improved sow and litter performance during summer.

Introduction

During lactation, maximizing sow feed intake is critical to reduce body reserve mobilization and sustain milk production for litter growth (Tokach et al., 2019). Lactation feed intake also affects sow longevity and subsequent reproductive performance (Patterson et al., 2011). However, sow farms located in warm and humid climates have difficulties maximizing lactation feed intake, which may lead to poorer performance of sows under heat stress (Bjerg et al., 2020; Zhang et al., 2022). Several factors can affect sow feed intake, including feeder type and environmental comfort (Tokach and Dial, 1992; Tokach et al., 2019; Bjerg et al., 2020). There are several types of lactation feeders for use in farrowing stalls. A good farrowing stall feeder should minimize feed wastage and spoilage and improve sow feed intake by enhancing the accessibility of feed and match the sow's feed intake pattern without causing pain or injury (Taylor, 1990; Peng et al., 2007; Choi et al., 2018). However, the difficulty of cleaning feeders also needs to be considered to avoid excess workload and cross-contamination of pathogens on the feeders to the next group of sows and litter.

In addition to feeder type, another factor influencing feed intake is environmental temperature. In hot environments, evaporative cooling can help reduce body temperature of swine (Godyń et al., 2020). Heat from the skin is dissipated through evaporation of sweat or water. Pigs have structures that morphologically conform with apocrine sweat glands in the skin but they do not sweat (Ingram, 1965) and therefore, cannot rely on evaporative cooling on their skin with sweat. Spray or drip cooling systems have been applied to provide skin evaporative cooling during warm weather. Drip cooling reduces the heat stress of a sow in a high-temperature environment and increases feed intake (Murphy et al., 1987; McGlone et al., 1988; Dong et al., 2001; Perin et al., 2016). However, there are few studies evaluating the effect of drip cooling in hot and humid environments. Furthermore, a limiting factor in drip cooling is high humidity. High humidity reduces the efficiency of evaporative cooling in removing heat (Godyń et al., 2020). Thus, it is theorized that drip cooling may not have significant effects on sows' performance in hot and humid areas. Therefore, the objective of this experiment was to evaluate the effect of lactation feeder type and drip cooling on lactating sow farrowing performance, litter growth, and feeder cleaning criteria in a hot and humid environment.

Material and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this study. The experiment was conducted at a commercial sow farm located in central Arkansas. There were 60 stalls per room. A total of 5 tunnel-ventilated farrowing rooms (300 stalls; 100 stalls per lactation feeder treatment) were used for each group. Evaporative cool cells were installed in all farrowing rooms and started circulating water at 26°C. Each farrowing crate was equipped with a bowl waterer. The trial was conducted in 2 sequential groups for a

total of 600 mixed parity sows (Line 3, PIC, Hendersonville, TN). The first group of sows farrowed between June 6 and 18, 2021, and the pigs were weaned between June 24 and July 7, 2021. The second group of sows farrowed between July 2 and 15, and the pigs were weaned between July 25 and August 4, 2021. Daily high and low temperatures were recorded inside the rooms for the duration of this study (Figure 5.1). Relative humidity data was not recorded by room; therefore, data were retrieved from the closest weather station (17 km away), CXW weather station (Conway, AR; Figure 5.1). For the first group of sows (June 6 to July 7, 2021), the average daily temperature ranged between 22.0 to 27.1°C with an average of 24.5°C and the average daily relative humidity ranged between 58.9 to 96.6% with an average of 71.9%. For the second group of sows (July 2 to August 4, 2021), the average daily temperature ranged between 21.5 to 27.1°C with an average of 24.7°C and the average daily relative humidity ranged between 62.6 to 95.0% with an average of 75.1%.

Animals and sow lactation feeders

Sows were inseminated with PIC line 2 (441 sows) and line 3 (159 sows) semen. At approximately d 110 to 112 of gestation, sows were moved from the gestation facility to the farrowing house, and blocked by body condition score (BCS), parity, and offspring sire line, then randomly allotted to farrowing stalls equipped with 1 of 3 feeder types with sow as the experimental unit. The 3 feeder types were; 1) PVC tube; 2) Rotecna ball feeder (Rotecna, Agramunt, Spain); or 3) SowMax ad-lib sow feeder (SKU: 7150890500; Hog Slat, Newton Grove, NC, Figure 5.2). The PVC tube feeders were the existing feeders in this sow farm. New Rotecna and SowMax feeders were installed for this trial. All farrowing stalls had the same feeder bowl type. The feeder bowl height and width were 55.9 and 35.6 cm, respectively, with a 10.2 cm depth from the front tip to the base. Moreover, with the specific feed hopper design of

each feeder type, the Rotecna feeder could hold approximately 12 kg of feed, and the SowMax feeder and the PVC tube feeder could hold approximately 10 kg of feed. The PVC tube feeder consisted of a 7.6-cm-diameter PVC tube installed perpendicularly to the base of the feeder bowl in the back-left corner. The feeder adjustment for the PVC tube feeder was conducted by adjusting the gap size between the bottom of the PVC tube opening and the inside of the base of the feeder bowl to control the feed flow from the feed hopper. As there was no mechanism to restrict the feed from flowing into the feeder bowl, sows did not need to trigger any mechanism and had continual access to feed in the bowl. The Rotecna feeder consisted of a round plastic bracket with a moveable ball structure at the bottom of the feeder. This was installed on the farrowing stall headgate with the bottom of the plastic bracket matching approximately the top edge of the feeder bowl. For feed delivery, sows were required to push up the ball, which opened a gap between the plastic bracket and the ball that allowed the feed to flow from the feed hopper to the feeder bowl. When pushed all the way up, the top of the ball stopped the feed flow by closing the gap at the bottom of the feeder hopper. When not triggered or pushed on by the sows, the ball dropped and closed the bottom-gap stopping the flow of feed. The amount of feed dropped from the Rotecna feeder was controlled by adjusting the distance (space) between the top- and bottom-gap. On the front side of the plastic bracket, there were 7 settings from 0 to 6 with 0 fully closed restricting all feed flow and 6 allowing the greatest amount of feed to flow to the bowl when triggered by the sow. The SowMax feeder consisted of a rectangular metal box with a rod-like structure at the bottom of the feeder. This was installed on the farrowing stall headgate with the bottom of the metal box matching approximately the top edge of the feeder bowl. For feed delivery, sows were required to push the rod from side to side, which moved internal parallel plates that allowed feed to drop from the feed hopper to the feeder bowl. When

not triggered by the sows, the plates restricted the feed from flowing to the feeder bowls. The adjustment for the SowMax feeder was controlled by adjusting the distance between the plates. On the side of the metal box, there were 6 distance settings from 0 to 5 with 0 fully closed constricting all feed flow and 6 allowing greatest feed flow when triggered by sow. The 3 feeder types were placed in the farrowing stalls in the same sequence (Rotecna, SowMax, and then PVC tube feeder) from the front to the end of all farrowing rooms to balance the environmental effect in each room (Figure 5.3). For the drip cooling evaluation, the trial was conducted during the second group of 300 sows. Water drippers were located above the stall and aimed at the shoulder of the sow. The setpoint of the drip cooling system initiated at 24°C and the system ran on a 10-min cycle (2 min on and 8 min off). Water drippers were disabled in 3 of every 6 farrowing stalls and the sequence changed between rows to balance the feeder types and the environmental effect in each room (Figure 5.3).

The same corn-soybean meal-based lactation feed was fed to all sows. During the pre-farrowing period, sows were provided approximately 0.91 kg in the morning and 0.91 kg during late afternoon, for a total of 1.82 kg per day of the lactation diet. After farrowing, sows were provided ad libitum access to feed. The hopper of each feeder type was filled to the top with lactation diet at least twice a day throughout the experimental period to provide sows with feed at all times. Feeder adjustments were made daily to achieve approximately 40 to 60% feed coverage on the base of the feeder bowl. Wet or moldy feed was removed from the feeder bowl when necessary. The spoiled feed was not weighed and defined as part of the total feed disappearance. Viable pigs from sows bred to Line 2 sires (7,562 pigs from 441 sows) were individually tagged with a RFID tag within 24 h of birth. Line 3 sired pig data was not collected as both of their ears were occupied with the farm's specific breeder tags and did not have space

left for the LeeO RFID tags; therefore, these line 3 sired pig data was not included in the litter performance data. However, the sows of these pigs were included in the sow BW and feed disappearance data. If cross-fostering was needed, pigs were cross-fostered within 24 h of birth and within feeder type and offspring sire line. The weaning age was between 19 and 22 d.

Data and sample collection

All animal and feed scales used in this trial were calibrated and verified with test weights to assure accuracy. The experiments' sow and litter data were recorded and stored using the LeeO system (Prairie Systems, Spencer, IA). An RFID tag was attached to each sow stall and identified as a location pen in the LeeO system. For sow data, the information (sow ID, parity, breeding date, and offspring sire line) of each sow was exported from the PigChamp system (Ames, IA) and then imported into the LeeO system. A walk-on platform scale was used to weigh sows before entering the farrowing house and at weaning. When sows were placed in the farrowing stall, they were also registered in the location pens in the LeeO system. The sow record cards were checked to assure the LeeO electronic system recorded and stored the data correctly. Feed carts equipped with scales were used to obtain the weight of each feed addition. Each feed addition was registered to the stall (location pen) with the date and weight recorded for calculating total feed disappearance data. Total feed disappearance was calculated by subtracting leftover feed in the feed hoppers at weaning from the cumulative feed addition during the lactation period. Total sow feed disappearance would represent the combination of feed intake as well as feed wastage. Subsequent sow performance data was obtained from the PigChamp system. Sows that were culled due to age, structural problems, or death were not included in the subsequent farrowing data analysis. For litter performance, viable Line 2 sired pigs were registered under the sow and location pen, and individually weighed at birth and at weaning.

Nonviable pigs (low birth weight or dead before ear tagging), stillborn, and mummies were recorded but not weighed. Any cross-fostering and mortalities throughout the lactation period were recorded. The data for pigs from sows bred to Line 3 sires were not collected; however, the sows of these pigs were included in the sow BW and feed disappearance data. Although there were differences in sample sizes, the treatments were still well balanced in terms of replication, BCS, sire line, and parity (Table 5.1 and 5.2) for the measurements.

After weaning, 3 farm employees were designated to wash feeders and record cleaning times for several feeders per feeder type. The number of feeders used was 19, 23, and 25 for the PVC tube, Rotecna, and SowMax feeder, respectively. For economic data, the lactation feed cost was USD 0.29/kg, litter value was USD 1.54/kg of litter weight, and the labor cost for cleaning was USD 15/h.

Statistical analysis

Data were analyzed as a randomized complete-block design for one-way ANOVA in R program (R core team, 2022; Vienna, Austria). Sow (litter) or feeder (cleaning criteria) were considered as the experimental unit. Groups and farrowing rooms were the blocking factors for sow and litter data. Cleaning personnel was used as the blocking factor for the cleaning criteria. Feeder type and drip cooling were used as the fixed effect. The lmer function from the lme4 package was used for lactating sow BW, feed disappearance, litter growth performance, cleaning criteria, and economics. The glmer function (Poisson distribution) from the lme4 package was used for total born, litter size after cross-fostering, live born, viable live born, and pigs weaned. The glmer function (negative binomial distribution) from the lme4 package was used for nonviable live born, stillborn, mummies, and subsequent total born. The glmer function (binomial distribution) from the lme4 package was used for subsequent farrowing rate, and bred

by 7, 14, and 30 d data. The glmmTMB function (beta-binomial distribution) from the glmmTMB package was used for pre-weaned mortalities. Sow entry weight was used as a covariate for weaning weight and weight change. Total born was used as a covariate for farrowing performance at birth. Litter size at 24 h after cross-fostering was used as a covariate for litter growth performance and litter economic data. These covariates were used when they significantly improved ($P < 0.05$) the models based on Bayesian information criterion. For both groups of sows, there was no interaction ($P > 0.10$) between treatments (feeder types or drip cooling settings) and female type (gilt or sow) for all response variables (Data not shown). A Tukey/Sidak multiple comparison adjustment was used when appropriate. All results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results

Sow and litter performance

For the effect of sow lactation feeder, there was no evidence of difference ($P > 0.10$) in sow entry BW, weaning BW, BW change, and litter performance (Table 5.1). The results from all sows showed that sows fed with SowMax feeders had decreased ($P < 0.05$) total feed disappearance, average daily feed disappearance, and total feed cost compared to sows fed with the PVC tube feeders, while the results of sows fed with the Rotecna feeders were intermediate. Moreover, the results from sows with litter data showed that sows fed with SowMax feeders had decreased ($P < 0.05$) total feed disappearance, average daily feed disappearance, and total feed cost compared to sows fed with either the PVC tube or Rotecna feeders. Therefore, litter feed efficiency, feed cost per pig weaned, and feed cost per kg of litter weight gain were improved ($P < 0.05$) for sows fed using the SowMax feeders compared to sows fed with either the PVC tube or Rotecna feeders. There was no evidence of difference ($P > 0.10$) in subsequent reproduction

performances (percentage bred by 7, 14, and 30 d after weaning, subsequent farrowing rate, and subsequent total born) between feeder types.

For the effect of drip cooling, sows provided with drip cooling had greater ($P < 0.05$) weaning BW, total feed disappearance, average daily feed disappearance, feed cost, and feed cost per pig weaned, and decreased ($P < 0.05$) BW change and percentage BW change (Table 5.2). There was no evidence of difference ($P > 0.10$) in litter criteria at farrowing, except sows without drip cooling had a greater ($P = 0.042$) percentage viable live born than sows with drip cooling. At weaning, litter weaning weight, pig weaning weight, litter weight gain, and litter ADG of sows provided drip cooling were greater ($P < 0.05$) than sows without drip cooling. There was no evidence of difference ($P > 0.10$) in litter feed efficiency, percentage weaned pigs, or mortalities. For subsequent reproduction performance, sows provided drip cooling had an increased ($P = 0.009$) subsequent total born compared to sows without drip cooling with no evidence of differences ($P > 0.10$) in subsequent farrowing rate and percentage of bred by 7, 14, and 30 d after weaning.

Cleaning criteria

Rotecna ball feeders tended to have a greater ($P < 0.10$) cleaning time and cleaning cost compared to the PVC tube feeders (Table 5.1); however, the results were highly variable among the people who washed the feeders (Figure 5.4). Regardless of the feeder type, the range of cleaning time per stall for the 3 people was from 30 to 71 s (person 1), 30 to 39 s (person 2), and 40 to 102 s (person 3), respectively.

Discussion

Feeder type

The setup of this study only allowed us to collect feed disappearance data, which is a combination of feed intake and feed wastage. However, because there was no evidence of

differences in sow body weight change and litter performance between feeder types, we speculate that sows fed with any of the feeder types had similar actual feed intake. Therefore, the differences in feed disappearance might have been affected by the differences in feed wastage between feeder types. Because the only mechanism for the PVC tube feeder type to control feed flow is the gap size between the bottom of the PVC tube and the base of the feeder bowl, the PVC tube has an almost continual flow without restriction. On the other hand, the SowMax and Rotecna feeders require sows to trigger the feed drop mechanism to deliver feed to the base of the feeder bowl. Our target during this study was to maintain feed coverage of the bowl to be 40 to 60 % covered. Though the feed coverage was not recorded, we observed that the feeder bowls of the PVC tube feeders had a greater frequency of excessive feed coverage than the other feeder types, even with daily adjustment. Additionally, the Rotecna and SowMax feeders can be easily adjusted to prevent excessive feed in the feeder bowl. When sows are eating, excessive feed in the feeder bowl might have a higher chance of being pushed out and resulting in feed wastage. Therefore, PVC tube feeders used in this study resulted in greater feed disappearance than the SowMax feeders with the Rotecna feeder intermediate. Moreover, excessive feed in the feeder bowl has a greater chance of spoiling and being contaminated because of exposure to water and saliva. Spoiled feed may cause feed refusal and reduce sow performance (Kanora and Maes, 2009). Peng et al. (2007) evaluated a self-fed feeder with ball mechanism similar to the Rotecna feeder. They observed that the self-fed feeders had a greater ($P < 0.05$) feed disappearance but improved ($P < 0.05$) litter performance compared to the hand-fed sows; however, their trial was conducted during the fall and winter seasons and the self-fed feeders used were wet-dry feeders while the hand-fed feeders were not. Moreover, because of the limited number of feedings per day, hand-fed sows might not have had access to feed at all times compared to sows with the

self-fed feeders that had feed storage hoppers. They concluded that the improvement was a consequence of sows having the choice of when to eat and the desired moisture level. Choi et al. (2018) also observed sows with an electronic self-fed feeders had greater ($P < 0.05$) feed intake and piglet ADG and reduced ($P < 0.05$) BW change compared to conventional feeders during summer. They suggested that it was due to the fermentation of residual feed in the conventional feeders that caused feed refusal. One concern about self-fed feeders is whether sows can learn how to operate them effortlessly. In our trial, sows had access to the feeders 1 to 3 d before farrowing to be familiar with the feeders. Farm staff were cognizant of any feed intake problems and were instructed to trigger the Rotecna or SowMax feeders if it was apparent a sow was not eating.

Another concern about different feeder types is the difficulty of cleaning which affects the cleanliness and the labor required (time and cost). We observed differences in the time required to wash a feeder, but we also observed large variation between people responsible for washing the feeders. This variation may come from the difference in the experience of cleaning and the personal standards of cleanliness. One potential confounding factor on cleaning time was that the farm crew had more experience cleaning the PVC tube feeders than the SowMax and Rotecna feeders, which might have unintentionally given PVC tube feeders an advantage in reducing cleaning time.

Drip cooling

Contrary to the theory that drip cooling may have no benefit in a hot and humid environment, our results suggest that drip cooling improved sow and litter performance. For sows with drip cooling, feed disappearance was increased, which led to greater feed cost and feed cost per pig weaned; however, these sows had reduced BW loss and improved lactation

performance, indicated by the greater weaning pig weight and litter value. Moreover, we also observed that sows with drip cooling had an increase in the number of total born in the subsequent farrowing compared to sow without drip cooling. Other research has observed that drip cooling reduced ($P < 0.05$) sow body temperature, respiration rate, and BW loss, and increased ($P < 0.05$) feed intake and litter weaning weight in warm and humid environments (Murphy et al., 1987; Dong et al., 2001). In a hot and dry environment (approximately 40% relative humidity), McGlone et al. (1988) observed that lactating sows with drip cooling had increased ($P < 0.05$) feed intake and reduced ($P < 0.05$) BW change and respiration rate during heat stress. These results suggest that sows with drip cooling experienced less heat stress than sows without drip cooling in hot environments. Similarly, sprinkler systems in a finishing facility increased ($P < 0.05$) ADG and reduced ($P < 0.05$) respiration rate of pigs compared to a control without cooling systems in farm located in a humid tropical area (Huynh et al., 2006). In addition, Barbari and Conti (2009) observed that sows preferred areas with high air velocity and drip cooling more than areas with only high air velocity or only drip cooling when they were housed in a hot and humid environment. Our study also suggests that drip cooling could be advantageous in hot and humid environments where the facility is tunnel-ventilated and has high air velocity.

In conclusion, the SowMax feeder appeared to reduce feed wastage without limiting sow feed intake. This resulted in improved production efficiency and economic savings. Moreover, drip cooling increased sow feed disappearance which improved sow and litter performance in a hot and humid environment. These results provide information on management practices that can improve sow farm production.

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Table 5.1. The effect of sow lactation feeder type on sow and litter performance[1].

Item	PVC tube	Rotecna	SowMax	SEM	*P*-value
Sow body weight (Line 2 and 3 sire)					
n	157	153	151	---	---
Parity	2.8	3.0	2.9	---	---
Entry, kg	223.2	221.4	225.1	4.59	0.580
Weaning, kg[2]	194.0	194.9	193.6	2.75	0.725
Weight change, kg[2]	-31.4	-30.6	-31.8	2.75	0.725
Weight change, %[2]	14.1	13.7	14.2	1.22	0.724
All sow feed disappearance (Line 2 and 3 sire)					
n	198	194	191	---	---
Parity	3.0	3.1	3.0	---	---
Total feed disappearance, kg	134.7[a]	130.4[ab]	127.6[b]	6.50	0.056
Daily feed disappearance, kg	6.3[a]	6.1[ab]	5.9[b]	0.31	0.027
Lactation feed cost, $[3]	39.34[a]	38.09[ab]	37.26[b]	1.899	0.055
Sows with litter performance (Only Line 2 sire)					
n	145	145	142	---	---
Parity	3.5	3.6	3.5	---	---
Lactation length, d	21.5	21.5	21.5	0.43	0.994
Total feed disappearance, kg	142.2[a]	139.5[a]	131.9[b]	8.06	0.003
Daily feed disappearance, kg	6.6[a]	6.5[a]	6.1[b]	0.37	0.002
Lactation feed cost, $[3]	41.55[a]	40.74[a]	38.52[b]	2.354	0.003
Total born, n	17.5	17.2	16.8	0.35	0.356
Live born, n[4]	15.4	15.7	15.3	0.33	0.729
Viable live born, n[4]	14.0	14.5	13.9	0.32	0.418
Nonviable live born, n[4,5]	1.3	1.1	1.3	0.12	0.450
Stillborn, n[4]	1.1	0.9	1.2	0.11	0.215
Mummified, n[4]	0.2	0.2	0.1	0.04	0.389
Litter birth weight, kg[4]	20.1	20.1	19.7	0.37	0.600
Pig birth weight, kg[4]	1.5	1.4	1.4	0.02	0.156
Litter size at 24 h, n[4]	14.4	14.8	14.1	0.32	0.271
Litter weaning weight, kg[6]	73.3	74.6	74.4	2.43	0.588
Pig weaning weight, kg[6]	5.7	5.8	5.8	0.16	0.328
Litter weight gain, kg[6]	53.2	54.8	54.5	2.55	0.406
Litter average daily gain, kg[6]	2.5	2.5	2.5	0.11	0.452
Weaned, n[6]	12.9	12.9	12.9	0.31	0.991
Pre-weaned mortalities, % of live born[7]	18.7	17.9	16.8	1.09	0.440
Pre-weaned mortalities, % of litter size at 24 h[8]	10.5	11.0	9.3	0.83	0.285
Litter feed efficiency[9]	0.39[a]	0.40[ab]	0.42[b]	0.074	0.021
Litter value, $[3,6]	113.15	115.05	114.78	3.752	0.588
Litter value over lactation feed cost, $[6]	71.39[y]	74.34[xy]	76.06[x]	1.777	0.060
Feed cost per pig weaned, $[6]	3.26[a]	3.22[ab]	3.02[b]	0.172	0.014
Feed cost per kg of litter weight gain, $	0.82[a]	0.77[ab]	0.74[b]	0.021	0.031
Sow subsequent performance (Line 2 and 3 sire)[10]					
n	189	184	180	---	---
Parity	2.9	3.0	2.9	---	---
Bred by 7 d, %	80.0	76.3	78.5	3.81	0.395
Bred by 14 d, %	81.5	78.3	78.9	3.54	0.336
Bred by 30 d, %	95.2	93.6	94.4	2.27	0.257

Subsequent farrowing rate, %	90.4	89.4	85.4	2.98	0.314
Subsequent total born, n	16.2	16.2	16.0	0.40	0.901
Feeder cleaning criteria					
n	19	23	25	---	---
Time per feeder, sec	43.6^{y}	53.3^{x}	51.0^{xy}	10.01	0.053
Cleaning cost per feeder, $[3]	0.18^{y}	0.22^{x}	0.21^{xy}	0.042	0.053

[1] A total of 600 mixed parity sows (PIC, Line 3) that were bred to Line 2 and Line 3 sires were used with 200 sows per treatment. Pigs of sows bred to Line 2 sires were included in the litter performance data. Sows were weighed on d 110, 111, or 112 of gestation, blocked by parity category and BCS, and allotted to treatment stalls at the time of entry to the farrowing house.

[2]Entry BW was used as a covariate.

[3]Lactation feed cost was USD 0.29/kg, and the labor cost for cleaning was USD 15/h. Litter value = litter weaning weight × USD 1.54/kg.

[4]Total born was used as a covariate.

[5]Nonviable pigs were pigs with low birth weight or dead before ear tagging.

[6]Litter size at 24 h after cross fostering was used as a covariate.

[7]Pre-weaned mortalities, % of live born = [(Total dead after birth)/(Viable live-born + nonviable live-born)] × 100%

[8]Pre-weaned mortalities, % of litter size = [(Dead after cross-fostering)/(Litter size at 24 h)] × 100%

[9]Litter feed efficiency = Total litter weight gain/ total feed disappearance.

[10]Subsequent performance data was obtained approximately one month after weaning. Sows that were culled due to old age, structural problems, or death were not included.

[a,b] Means within a row with different superscripts differ ($P \leq 0.05$).

[x,y] Means within a row with different superscripts differ ($0.05 < P \leq 0.10$).

Table 5.2. The effect of drip cooling on sow and litter performance[1].

Item	Drip cooling		SEM	*P*-value
	Without	With		
Sow body weight (Line 2 and 3 sire)				
n	124	121	---	---
Parity	2.9	2.9	---	---
Entry, kg	217.3	218.7	7.98	0.731
Weaning, kg[2]	188.9	192.5	3.13	0.028
Weight change, kg[2]	-34.1	-30.5	3.13	0.028
Weight change, %[2]	15.5	13.9	1.41	0.023
All sow feed disappearance (Line 2 and 3 sire)				
n	149	145	---	---
Parity	3.1	3.2	---	---
Total feed disappearance, kg	121.3	135.2	8.62	< 0.001
Daily feed disappearance, kg	5.5	6.2	0.40	< 0.001
Lactation feed cost, $[3]	35.46	39.50	2.52	< 0.001
Sows with litter performance (Only Line 2 sire)				
n	108	111	---	---
Parity	3.5	3.7	---	---
Lactation length, d	21.9	21.9	0.57	0.926
Total feed disappearance, kg	127.0	144.4	9.98	< 0.001
Daily feed disappearance, kg	5.8	6.6	0.41	< 0.001
Lactation feed cost, $[3]	37.10	42.17	2.91	< 0.001
Total born, n	17.6	17.6	0.40	0.989
Live born, n[4]	15.9	15.7	0.38	0.754
Viable live born, n[4]	14.6	14.4	0.37	0.592
Nonviable live born, n[4,5]	1.2	1.3	0.14	0.351
Stillborn, n[4]	1.0	1.3	0.14	0.204
Mummified, n[4]	0.2	0.3	0.06	0.554
Litter birth weight, kg[4]	20.6	20.0	0.40	0.201
Pig birth weight, kg[4]	1.4	1.4	0.02	0.371
Litter size at 24 h, n[4]	14.8	14.5	0.37	0.610
Litter weaning weight, kg[6]	71.7	75.0	3.25	0.034
Pig weaning weight, kg[6]	5.5	5.8	0.22	0.025
Litter weight gain, kg[6]	51.2	55.0	3.27	0.015
Litter average daily gain, kg[6]	2.3	2.5	0.11	0.012
Weaned, n[6]	12.9	13.0	0.35	0.846
Pre-weaned mortalities, % of live born[7]	18.2	18.4	1.20	0.890
Pre-weaned mortalities, % of litter size at 24 h[8]	11.4	10.2	0.95	0.332
Litter feed efficiency[9]	0.39	0.41	0.014	0.215
Litter value, $[3,6]	110.67	115.77	5.01	0.034
Litter value over lactation feed cost, $[6]	73.42	73.59	2.646	0.944
Feed cost per pig weaned, $[6]	2.90	3.27	0.223	< 0.001
Feed cost per kg of litter weight gain, $	0.77	0.82	0.029	0.234
Sow subsequent performance (Line 2 and 3 sire)[10]				
n	145	134	---	---
Parity	3.0	3.0	---	---
Bred by 7 d, %	74.6	74.7	3.96	0.987
Bred by 14 d, %	75.4	77.7	3.96	0.644
Bred by 30 d, %	97.3	93.8	3.0	0.120

Subsequent farrowing rate, %	83.0	85.8	3.17	0.522
Subsequent total born, n	15.2	16.8	0.59	0.009

[1] A total of 300 mixed parity sows (PIC, Line 3) that were bred to Line 2 and Line 3 sires were used with 150 sows per treatment. Pigs of sows bred to Line 2 s were included in the litter performance data. Sows were weighed on d 110, 111, or 112 of gestation, blocked by parity category and BCS, and allotted to treatment stalls at the time of entry to the farrowing house.

[2]Entry BW was used as a covariate.

[3]Lactation feed cost was USD 0.29/kg, and the labor cost for cleaning was USD 15/h. Litter value = litter weaning weight × USD 1.54/kg.

[4]Total born was used as a covariate.

[5]Nonviable pigs were pigs with low birth weight or dead before ear tagging.

[6]Litter size at 24 h after cross fostering was used as a covariate.

[7]Pre-weaned mortalities, % of live born = [(Total dead after birth)/(Viable live-born + nonviable live-born)] × 100%

[8]Pre-weaned mortalities, % of litter size = [(Dead after cross-fostering)/(Litter size at 24 h)] × 100%

[9]Litter feed efficiency = Total litter weight gain/ total feed disappearance.

[10]Subsequent performance data was obtained approximately one month after weaning. Sows that were culled due to old age, structural problems, or death were not included.

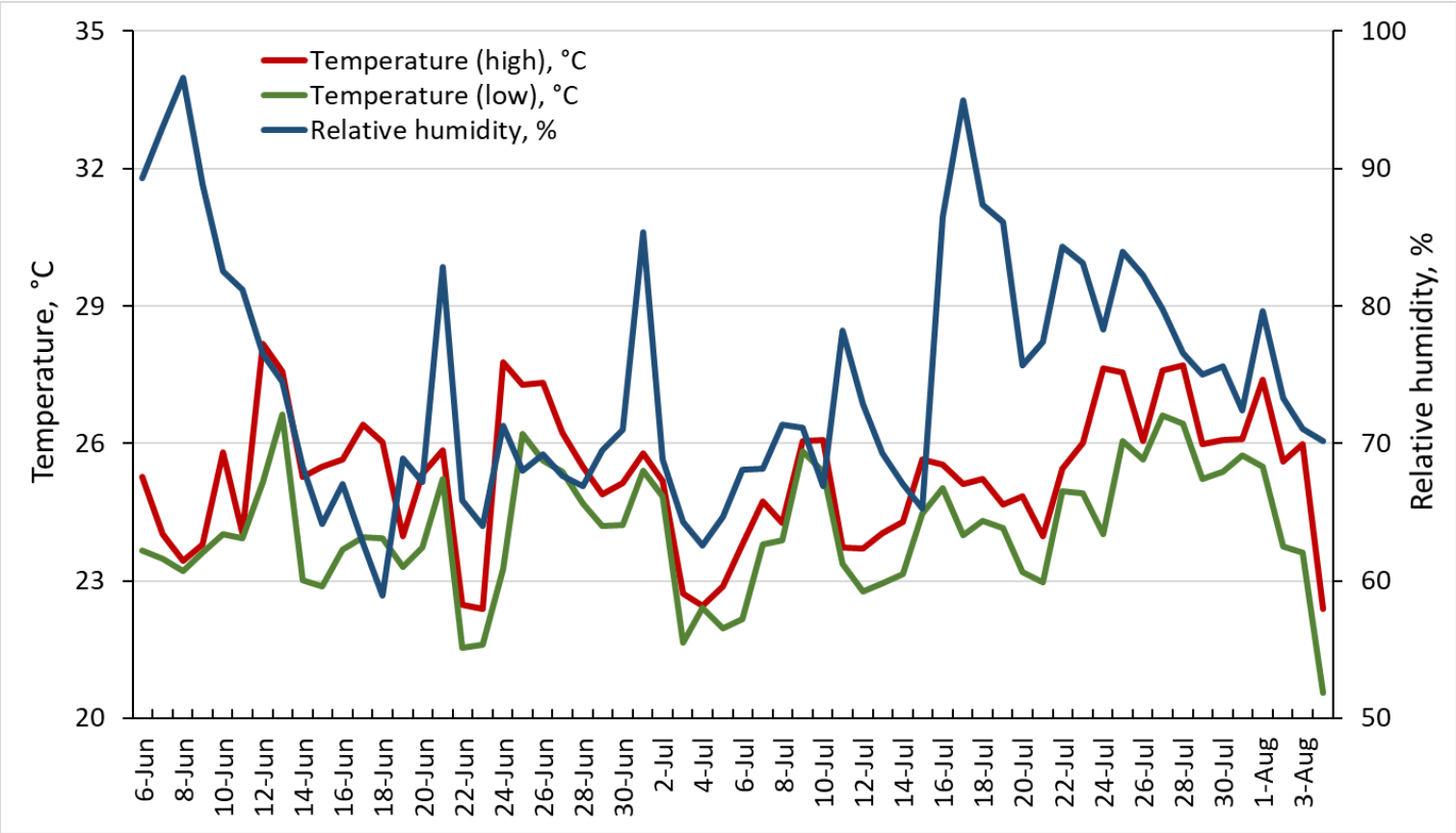

Figure 5.1. Room temperature and outdoor relative humidity data.

Daily high and low temperatures were recorded inside the rooms for the duration of this study, and the humidity data were retrieved from the closest weather station, CXW weather station (Conway, AR; 17 km away). For the first group of sows (June 6 to July 7, 2021), the average daily temperature ranged between 22.0 to 27.1°C with an average of 24.5°C and the average daily relative humidity ranged between 58.9 to 96.6% with an average of 71.9%. For the second group of sows (July 2 to August 4, 2021), the average daily temperature ranged between 21.5 to 27.1°C with an average of 24.7°C and the average daily relative humidity ranged between 62.6 to 95.0% with an average of 75.1%.

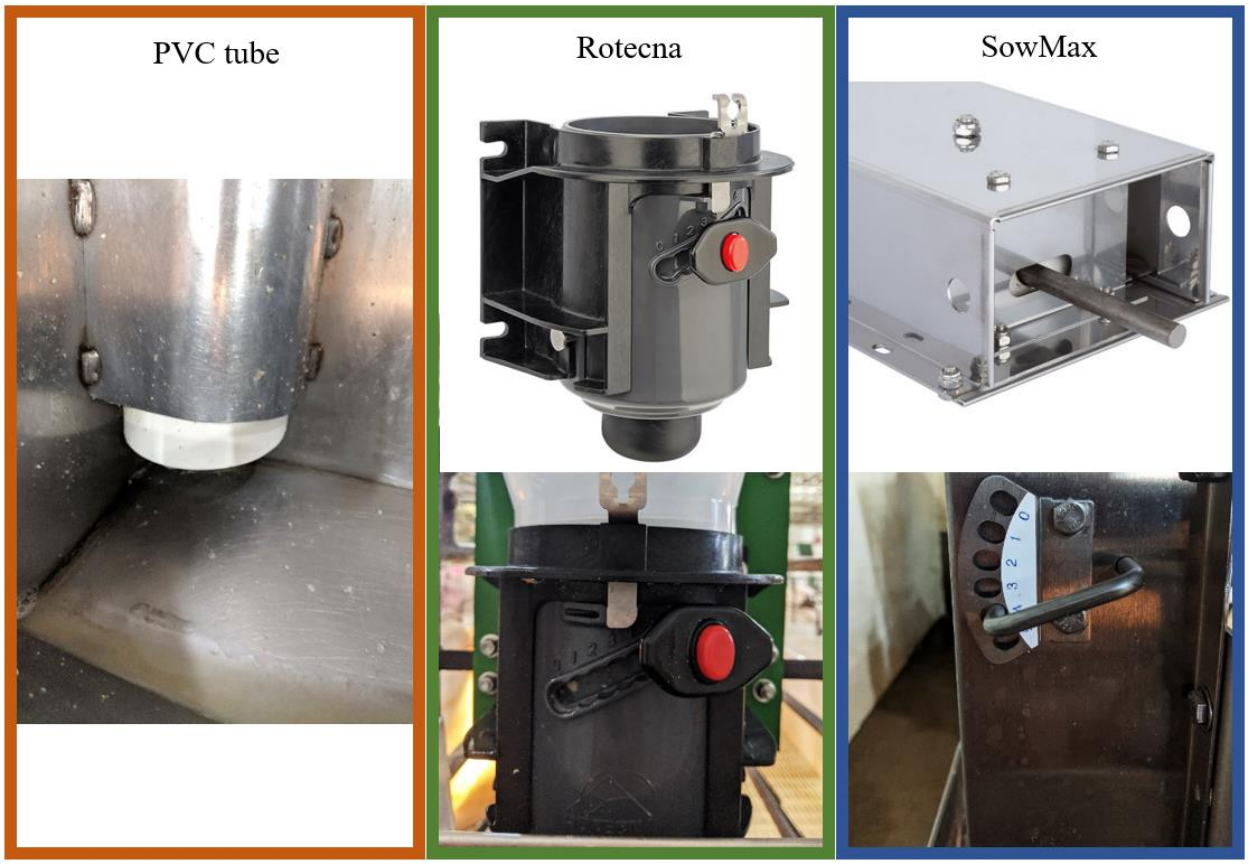

Figure 5.2. Sow lactation feeders, feeder trigger, and adjustment mechanisms.

For feeder adjustment, the PVC tubes were pushed against the feeder wall by a screw to maintain the gap between the end of the PVC tube and the bottom of the feeder bowl with friction. The Rotecna and SowMax feeders had quick adjustment handles to control the amount of feed dropped (gap size) for each trigger by the sows. For the trigger mechanism, Rotecna has a ball structure that can be pushed up from all directions and opens a gap to allow feed to drop. SowMax has a rod that can be pushed sideways and opens a gap on the sides of the hopper to allow feed to drop.

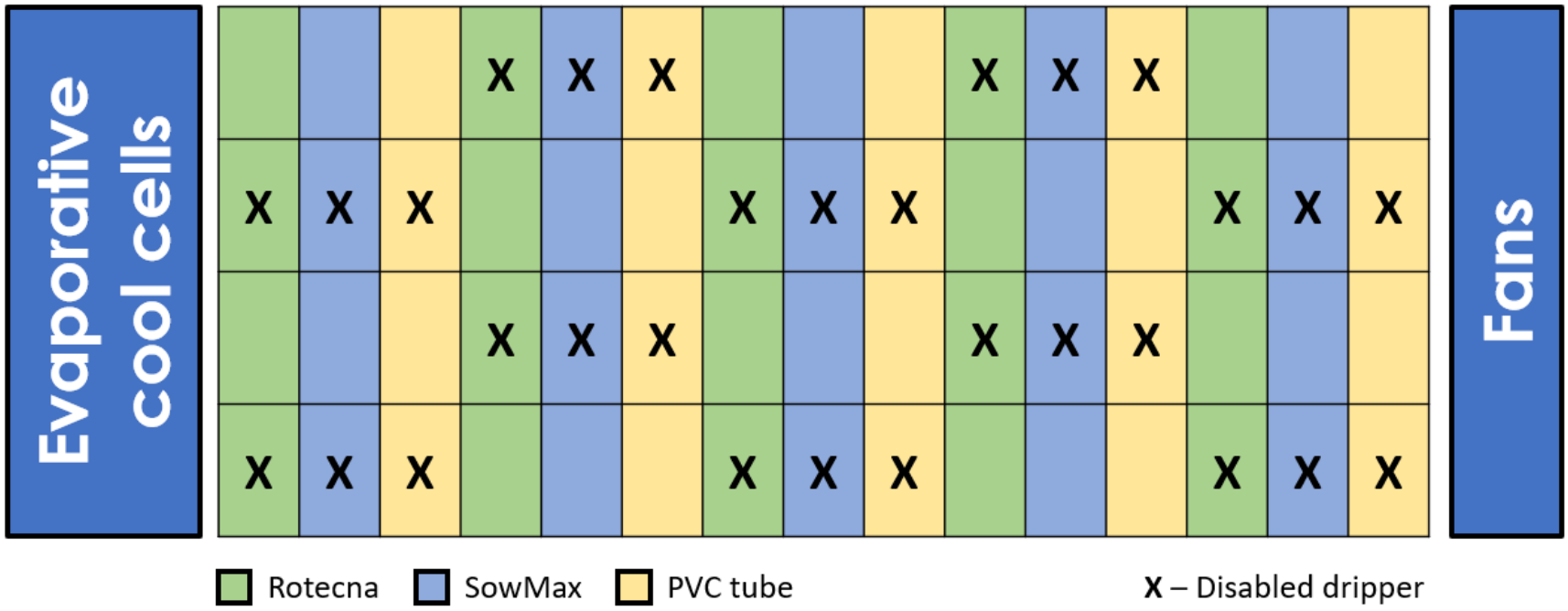

Figure 5.3. Example of lactation feeder type and drip cooling setup in a farrowing room.

Five rooms with 60 stalls per room were used. Every cell represents a farrowing stall. Rotecna, SowMax, and PVC tube feeders were installed in green, blue, and yellow cells, respectively. Water drippers were disabled in cells that contain an "X".

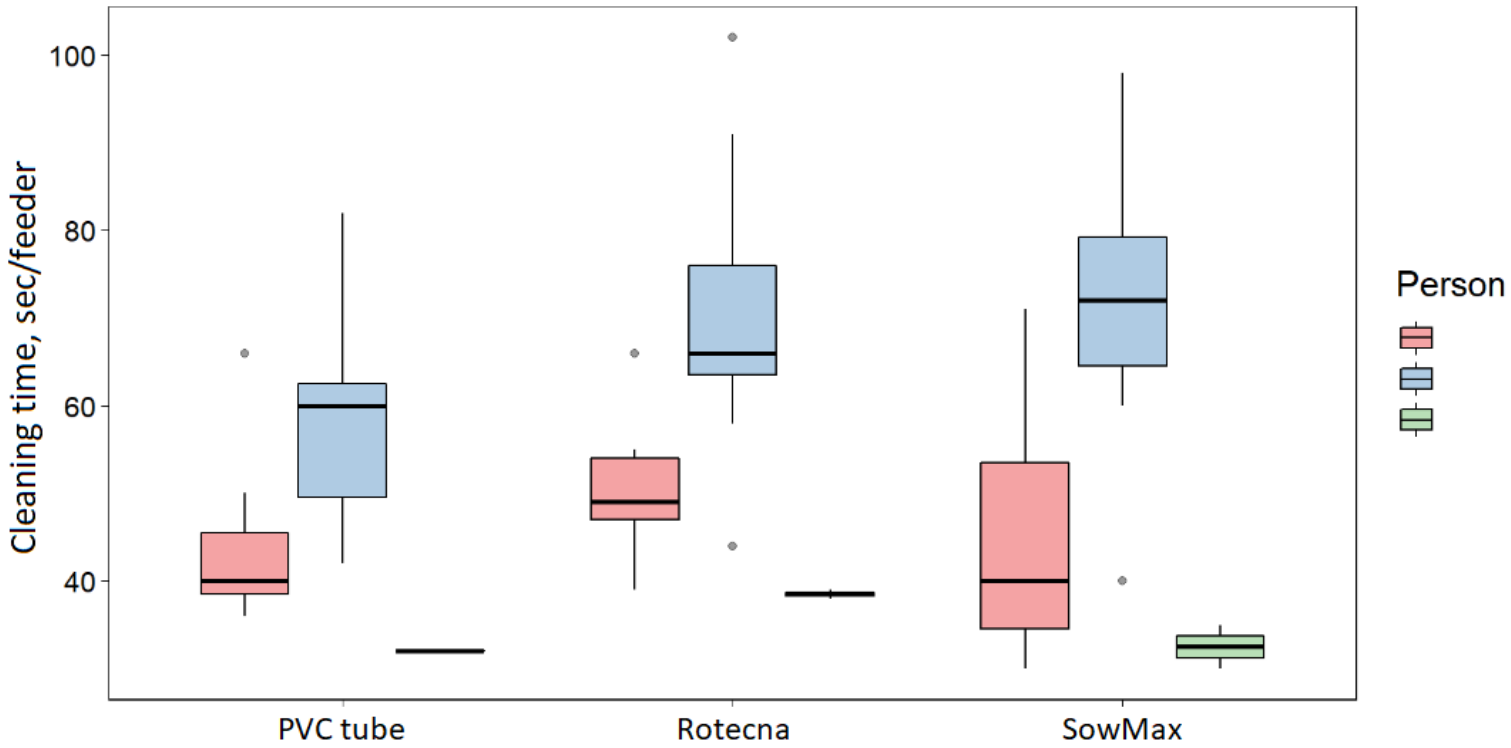

Figure 5.4. Feeder cleaning time per feeder by personnel.

After weaning, the feeders were washed by 3 farm employees and the cleaning times for several feeders per feeder type were recorded. The number of feeders used was 19, 23, and 25 for the PVC tube, Rotecna, and SowMax feeder, respectively. Each color represents a distinct farm employee. The results varied highly between the people who washed the feeders. The range of cleaning time for the 3 people was from 30 to 71 s (red), 40 to 102 s (blue), and 30 to 39 s (green), respectively.

Appendix A - Effects of various feed additives on finishing pig growth performance and carcass characteristics: A review - Supplemental material

Feed Additives – Health

This section discusses the feed additives that have the potential to improve growth performance and carcass characteristics by enhancing the health status of grow-finish pigs. The feed additives discussed are acidifiers, essential oils, DFM, yeasts, Cu, and Zn.

1. Acidifiers

There were 32 research articles for acidifiers with 68 comparisons from 16 countries during the grow-finish or finishing period which met the requirements for inclusion. Of these, 68 comparisons reported growth performance data and 42 comparisons reported carcass data. Most acidifiers collected for this review were organic acids that were in the form of short-chain fatty acids (**SCFA**; 39 comparisons), medium-chain fatty acids (**MCFA**; 1 comparison), and benzoic acid (10 comparisons), and were added alone or in combinations (SCFA and MCFA; 18 comparisons) from 0.05 to 5.0% in the diets.

1.1. Growth performance - Acidifiers

Average daily gain significantly increased ($P \leq 0.05$) in 18 comparisons (average of 5.8%) and significantly decreased ($P \leq 0.05$) in 4 comparisons (average of 10.8%) compared to control pigs (Table

A.1). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (46 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 31 comparisons (average of 3.4%) and numerically decreased in 15 comparisons (average of 3.4%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 13 comparisons (average of 6.4%) and significantly decreased ($P \leq 0.05$) in 1 comparison (9.7%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (51 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 40 comparisons (average of 3.8%) and numerically decreased in 9 comparisons (average of 3.1%) compared to control pigs. By comparing different acid types, acid blends and benzoic acids improved ADG more than SCFAs, while acid blends and SCFA improved G:F more than benzoic acid. Compared to control pigs, those fed acidifiers had 4.1% (18 comparisons), 2.8% (10 comparisons), and 0.3% (39 comparisons) improvement in ADG when fed acid blends, benzoic acid, and SCFA, respectively. Feed efficiency was improved by 4.2% (18 comparisons), 2.1% (10 comparisons), and 2.9% (39 comparisons) in pigs fed acid blends, benzoic acid, and SCFA, respectively, compared to control pigs. There were not enough data to support whether different types of basal diets and inclusion levels affected the response to acidifiers for ADG and G:F in grow-finish pig diets. In summary, feeding acidifiers has the potential to improve growth performance.

Table A.1. Studies on the effects of dietary acidifiers on growth performance

Author	Country	Acids	Inclusion, %	Sig.	Difference, %	
					ADG	G:F
Thacker and Bowland (1980)	Canada	Propionic acid	3.0	ns	-2.7	6.3
			6.0	ADG	-12.2	4.5
			9.0	ADG	-14.9	10.8
Thacker and Bowland (1981)	Canada	Propionic acid	3.5	ns	1.3	7.1
			7.0	ns	-3.8	5.9
		Calcium propionate	3.5	ns	4.8	6.6
			7.0	ns	-8.3	-6.8
Thacker et al. (1981)	Canada	Propionic acid	5.0[4]	ADG, G:F	-8.1	8.8
			5.0[4]	ADG	-7.9	6.1
Giesting and Easter (1985)	USA	Fumaric acid	1.5	ns[2]	2.5	-2.7
			3.0		7.6	0.0
Thacker et al. (1992)	Canada	Propionic acid	2.5	ns	-1.2	4.1
Baustad (1993), Exp. 1	Norway	Formic acid	0.6	ADG, G:F	11.4	11.3
			1.2	ns	5.3	6.2
Baustad (1993), Exp. 2	Norway	Formic acid	0.6	ADG, G:F	7.0	7.0
Baustad (1993), Exp. 3	Norway	Formic acid	0.6	ns	3.8	3.6
Krause et al. (1994)	USA	Fumaric acid	2.5	ns	2.3	3.6
Siljander-Rasi et al. (1998)	Finland	Formic acid	0.8	ns	1.4	1.0
Partanen et al. (2002)	Finland	Formic acid	0.8	G:F	4.7	4.9
		Formic acid and sorbate	0.8	ADG, G:F	8.6	9.9
Canibe et al. (2005)	Denmark	Formic acid	1.8	ns	9.0	5.4
Jansons and Nudiens (2005)	Latvia	Formic acid, acetic acid, citric acid, and phosphoric acid	0.6/0.4/0.3	ADG	5.9	n/a
Bühler et al. (2006)	Switzerland	Benzoic acid	1.0	ns	4.0	1.7
Campbell et al. (2006)	Ireland	Acid blend	0.3	ns	-5.4	-7.5
		Fumaric acid	0.2	ns	-8.1	-6.3
Partanen et al. (2006)	Finland	Sorbate-coated formic acid	0.3	ns	4.9	3.7
			0.6	ADG	6.4	3.7
			1.2	ADG, G:F	5.6	7.3

		Formic acid and lactic acid	0.3	ADG, G:F	6.4	5.5
			0.6	G:F	4.6	4.6
			1.2	G:F	5.4	5.0
Eisemann and Heugten (2007)	USA	Formic acid, ammonium formate	1.2/1.0	ns	-0.9	2.4
			1.0/0.8	ns	-0.1	5.2
			0.8/0.6	ns	0.9	3.9
			1.0	ns	2.9	3.4
			0.8	ns	-1.0	2.5
			0.6	ns	-1.4	2.3
Øverland et al. (2007)	Norway	Formic acid	1.0	ns	1.8	3.4
		Benzoic acid	0.85	ns	2.3	3.9
		Sorbic acid	0.85	ns	2.4	4.4
		Fat coated Ca-butyrate	1.2	ns	7.2	0.9
		Inulin coated Ca-butyrate	1.5	ns	-2.9	0.5
Guy et al. (2008)	UK	Formic acid and propionic acid	0.7/0.6/0.5/0.0.3	ns	-1.5	-0.9
		Formic acid, fumaric acid, and propionic acid	1.0/0.8/0.6/0.5/0.4	ns	-0.3	-1.3
Kijparkorn et al. (2009)	Thailand	Formic acid, lactic acid, citric acid, fumaric acid	0.4	G:F	-12.5	-9.7
Thacker and Haq (2009)	Canada	Propionic acid and acetic acid	1.0	ns	4.8	-0.7
Jansons et al. (2011)	Lativia	Formic acid, acetic acid, citric acid, and phosphoric acid	0.6/0.4/0.3[4]	ADG	6.2	n/a
			0.6/0.4/0.3[4]	ns	-1.3	n/a
Upadhaya et al. (2014)	South Korea	Fumaric acid, citric acid, malic acid, MCFA (capric and caprylic acid)	0.1	ADG[2]	3.9	2.8
			0.2		6.0	3.7
Cho et al. (2015)	South Korea	Benzoic acid	0.5	ns	0.1	-1.1
Giannenas et al. (2016)	Greece	Benzoic acid	0.5	ns	2.9	7.1
Zhai et al. (2017)	China	Benzoic acid	0.3	ADG[2], G:F[2]	5.9	3.1
			0.5		5.2	3.1
Lei et al. (2018)	South Korea	Fumaric acid, citric acid, malic acid, MCFA (capric and caprylic acid)	0.05	ns	3.1	4.7
			0.1	ns	5.4	6.3

Nguyen Thi (2018)	Vietnam	Fumaric acid, lactic acid, calcium formate, and phosphoric acid	0.2	ADG	5.6	4.3
Morel et al. (2019)	New Zealand	Benzoic acid	0.5	ns	0.5	0.7
		Butyrate	0.15	ns	2.4	0.3
Nguyen et al. (2019)	South Korea	Fumaric acid, citric acid, malic acid, MCFA (capric and caprylic acid)	0.1	ADG	4.1	4.5
			0.2	ADG, G:F	4.5	5.0
O' Meara et al. (2020)	Ireland	Benzoic acid	0.25	ns[2]	2.9	-0.9
			0.5		1.1	1.8
Tran Thi Bich et al. (2020)	Thailand	Formic acid, acetic acid, lactic acid, propionic acid, citric acid, and sorbic acid) and MCFAs	0.2	ADG, G:F	5.3	8.1
Muniyappan et al. (2021)	South Korea	Fumaric acid, citric acid, phosphoric acid, and malic acid	0.05	ADG[2]	2.5	1.4
			0.1		3.3	1.8
Tutida et al. (2021)	Brazil	Lactic, citric, and ascorbic acid	0.1/0.05	ns	0.0	0.0

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

1.2. Carcass Characteristics - Acidifiers

Back-fat significantly decreased ($P \leq 0.05$) in 3 comparisons (average of 12%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (21 comparisons; Table A.2). Of these, BF was numerically increased ($P > 0.10$) in 14 comparisons (average of 2.6%) and numerically decreased in 5 comparisons (average of 3.2%) compared to control pigs. For percentage lean, all comparisons found no evidence of difference ($P > 0.10$) in percentage lean. Of these, percentage lean was numerically increased ($P > 0.10$) in 9 comparisons (average of 0.9%) and numerically decreased in 15 comparisons (average of 1.4%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 2 comparisons (average of 6.3%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LAM/LD (9 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 7 comparisons (average of 2.6%) and numerically decreased in 2 comparisons (average of 6.9%) compared to control pigs. These results could be expected because the mechanisms do not directly affect the protein and lipid metabolism. Also, it appears that acidifiers' impacts on ADG and G:F were not great enough to affect carcass characteristics.

Table A.2. Studies on the effects of dietary acidifiers on carcass characteristics.

Author	Country	Acidifiers	Inclusion, %	Sig.	Difference, %			
					Yield	BF	percentage lean	LMA/LD
Thacker and Bowland (1980)	Canada	Propionic acid	3.0	ns	0.1	-2.4	n/a	n/a
			6.0	BF	2.2	-5.9	n/a	n/a
			9.0	BF	-3.5	-15.3	n/a	n/a
Thacker and Bowland (1981)	Canada	Propionic acid	3.5	ns	-0.4	0.9	n/a	n/a
			7.0	ns	-0.6	-2.6	n/a	n/a
		Calcium propionate	3.5	ns	-0.6	-6.6	n/a	n/a
			7.0	BF	-2.7	-14.8	n/a	n/a
Thacker et al. (1992)	Canada	Propionic acid	2.5	ns	-0.6	n/a	-0.6	n/a
Baustad (1993), Exp. 1	Norway	Formic acid	0.6	ns	n/a	n/a	-0.5	n/a
			1.2	ns	n/a	n/a	-1.6	n/a
Baustad (1993), Exp. 2	Norway	Formic acid	0.6	ns	n/a	n/a	4.2	n/a
Baustad (1993), Exp. 3	Norway	Formic acid	0.6	ns	n/a	n/a	0.8	n/a
Partanen et al. (2002)	Finland	Formic acid	0.8	ns	0.5	1.3	0.2	n/a
		Formic acid and sorbate	0.8	ns	0.0	1.3	0.3	n/a
Campbell et al. (2006)	Ireland	Acid blend	0.3	ns	-0.3	n/a	n/a	n/a
		Fumaric acid	0.2	ns	0.5	n/a	n/a	n/a
Partanen et al. (2006)	Finland	Sorbate-coated formic acid	0.3	ns	-0.1	6.2	-1.0	n/a
			0.6	ns	-0.8	0.0	-0.2	n/a
			1.2	ns	0.1	1.6	-0.3	n/a
		Formic acid and lactic acid	0.3	ns	-0.4	1.6	-0.3	n/a
			0.6	ns	0.0	2.3	-0.3	n/a
			1.2	ns	0.5	0.8	0.5	n/a
Øverland et al. (2007)	Norway	Formic acid	1.0	ns	0.4	n/a	-2.7	n/a
		Benzoic acid	0.85	Yield	2.3	n/a	-1.8	n/a
		Sorbic acid	0.85	ns	-0.3	n/a	-2.8	n/a
		Fat coated Ca-butyrate	1.2	ns	-0.1	n/a	-2.9	n/a
		Inulin coated Ca-butyrate	1.5	ns	-0.4	n/a	-3.6	n/a
Thacker and Haq (2009)	Canada	Propionic and acetic acid	1.0	ns	0.0	14.4	-1.7	4.1

Upadhaya et al. (2014)	South Korea	Fumaric acid, citric acid, malic acid, MCFA (capric and caprylic acid)	0.1	LMA[2]	n/a	n/a	n/a	4.6
			0.2		n/a	n/a	n/a	8.1
Nguyen Thi (2018)	Vietnam	Fumaric acid, lactic acid, calcium formate, and phosphoric acid	0.2	ns	-0.8	0.5	n/a	2.5
Morel et al. (2019)	New Zealand	Benzoic acid	0.5	ns	0.1	0.0	n/a	1.4
		Butyrate	0.15	ns	-0.4	1.1	n/a	3.4
Nguyen et al. (2019)	South Korea	Fumaric acid, citric acid, malic acid, MCFA (capric and caprylic acid)	0.1	ns	n/a	n/a	n/a	-7.2
			0.2	ns	n/a	n/a	n/a	-6.5
O' Meara et al. (2020)	Ireland	Benzoic acid	0.25	ns[2]	-0.1	3.6	-0.5	1.3
			0.5		-0.5	-0.7	0.5	2.6
			1.0		-0.9	-3.6	1.1	3.0
Muniyappan et al. (2021)	South Korea	Fumaric acid, citric acid, phosphoric acid, and malic acid	0.05	ns[2]	n/a	1.2	0.5	n/a
			0.1		n/a	2.2	0.1	n/a

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.
[2]Polynomial contrasts were used for statistical analysis.

2. Essential Oils (EO)

There were 13 research articles for EO with 20 comparisons from 6 countries during the grow-finish or finishing period with added dietary levels of 0.003 to 0.1%. Of these, 20 comparisons reported growth performance data and 17 comparisons reported carcass data. Essential oils used in these experiments were extracted from caraway, citrus, cinnamon, Chinese cinnamon, oregano, clove, clover, rosemary, fenugreek seed, eucalyptus, lemon, garlic, and *Eucommia ulmoides*. Because of the similar antibacterial properties between essential oils and acids, these two additives are sometimes blended as a single additive. Therefore, 5 more articles (5 experiments) from 4 countries with blended additives (EO and acids) were also included.

2.1. Growth Performance - Essential Oils

Average daily gain significantly increased ($P \leq 0.05$) in 10 comparisons (average of 9.9%) compared to control pigs (Table A.3). Half of the studies found no evidence of difference ($P > 0.10$) in ADG (10 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 6 comparisons (average of 3.8%) and numerically decreased ($P > 0.10$) in 3 comparisons (average of 1.7%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 7 comparisons (average of 10.9%) and tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (4.5%) compared to control pigs. Half of the studies found no evidence of difference ($P > 0.10$) in G:F (9 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 6 comparisons (average of 3.5%) and numerically decreased ($P > 0.10$) in 2 comparisons

(average of 1.5%) compared to control pigs. Overall, the results suggest that EO had positive effects on ADG and G:F (80 and 82% of all the comparisons). Moreover, the beneficial effects of EO were significant ($P < 0.10$) for ADG and G:F in 50 and 57% of all the comparisons, respectively. For EO and acid blends, there are only 7 comparisons for both ADG (average of 1.9% improvement) and G:F (average of 2.2% improvement). Of these, 71% of the comparison where pigs fed the additive had increased ADG (average of 3.8%) and G:F (average of 3.7%), and 29% of the comparisons had reduced ADG (average of 2.9%) and G:F (average of 1.5%) compared to control. There were insufficient data to support whether different types of basal diets and inclusion levels affected EO response for ADG and G:F. In summary, adding EO alone or in combination with acids has the potential to improve growth performance. However, there was only a small amount of research on EO's effect on growth performance, and only three studies were conducted in the US; therefore, the use of EO may not be beneficial in US-based conditions. More experiments are needed to determine the effect of including EO in the diets of grow-finish pigs.

Table A.3. Studies on the effects of dietary essential oils (EO) with or without acids on growth performance.

Author	Country	Additive	Inclusion, %	Sig.[1]	Difference, %[1]	
					ADG	G:F
Essential oils						
Onibala et al. (2001)	Indonesia	Oregano EO	0.0025	ADG, G:F	4.1	5.8
		Thyme EO	0.0025	ADG, G:F	8.8	6.5
		Garlic EO	0.0025	ADG, G:F	5.9	7.7
Yan et al. (2010)	South Korea	Thyme, rosemary, and oregano EO	0.01	ADG	6.6	6.6
Simitzis et al. (2010)	Greece	Oregano EO	0.025	ns	11.1	n/a
			0.05	ns	2.6	n/a
			0.1	ns	3.7	n/a
Zhou et al. (2016)	China	*Eucommia ulmoides* oliver leaf polyphenolic extract	0.08	ADG, G:F	18.8	19.9
Zou et al. (2016)	China	*Oregano EO*	0.0025	ADG, G:F	18.6	15.7
Li et al. (2017)	South Korea	Cinnamon, oregano, clove, thyme, and rosemary EO	0.05	ns	3.8	4.1
			0.05	ns	1.0	2.0
Soto et al. (2017)	USA	Caraway, garlic, thyme, and cinnamon	0.020	ns	-0.5	1.3
		Oregano, citrus, and anise	0.013	ns	0.5	1.0
		Caraway, garlic, thyme, cinnamon, oregano, citrus, and anise	0.033	ns	0.0	-0.3
Zou et al. (2017)	China	Oregano EO	0.0025	ADG, G:F	10.2	9.4
Cheng et al. (2018)	China	Oregano EO	0.025	ADG, G:F	10.6	11.0
Lan and Kim (2018)	South Korea	Fenugreek seed, clover, and Chinese cinnamon EO	0.01	ADG	5.0	5.9
Lowell et al. (2018)	USA	Oregano EO	0.025	ns	-2.9	0.0
Huang et al. (2021)	China	Eucalyptus, oregano, thyme, lemon, garlic EO	0.02	ADG, G:F[3]	10.3	4.5
Tutida et al. (2021)	Brazil	Thymol and Carvacrol	0.100	ns	-1.6	-2.6
Essential oils and Acidifier Blends						
Cho et al. (2014)	South Korea	Citric acids, sorbic acid, and EOs (thymol and vanillin)	0.025	ADG[2]	4.3	3.0
			0.05		4.0	3.0

Walia et al. (2017)	Ireland	Formic acid, citric acid, and EOs (citrus fruit extract, cinnamon, oregano, thyme, and capsicum)	0.4	ns	-4.6	-2.5
Oh et al. (2019)	South Korea	Citric acids, sorbic acid, and EOs (thymol and vanillin)	0.1/0.025[5] 0.2/0.05[5]	ADG[2], G:F[2]	2.2 5.4	2.7 5.9
Resende et al. (2020)	Brazil	Benzoic acid and EOs (thymol, 2-methoxyphenol, and eugenol)	0.3	ADG	3.3	3.8
Hutchens et al. (2021)	USA	Citric acids, sorbic acid, and EOs (thymol and vanillin)	0.3/0.1/0.054	ns	-1.2	-0.5

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]Feed additive was added at 0.3, 0.1% in nursery phase 1 and 2, respectively, and 0.05% in grow-finish phase.

[5]For the low inclusion treatment, feed additive was added at 0.1% in nursery phase and 0.025% in grow-finish phase. For the high inclusion treatment, feed additive was added at 0.2% in nursery phase and 0.05% in grow-finish phase.

2.2. Carcass Characteristics - Essential Oils

Back-fat significantly decreased ($P \leq 0.05$) in 3 comparisons (average of 2.7%) compared to control pigs (Table A.4). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (11 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 5 comparisons (average of 3.7%) and numerically decreased ($P > 0.10$) in 6 comparisons (average of 5.5%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in 3 comparisons (average of 2.5%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (6 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 3 comparisons (average of 1.2%) and numerically decreased ($P > 0.10$) in 2 comparisons (average of 1.5%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 3 comparisons (average of 7.1%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (7 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 4 comparisons (average of 1.0%) and numerically decreased ($P > 0.10$) in 3 comparisons (average of 2.3%) compared to control pigs. For essential oils and acid blends, there are only 3 experiments, and the effects on carcass characteristics were small and not statistically significant [BF (average of 0.5% improvement); percentage lean (average of 1.7% improvement); and LMA (average of 0.1% improvement)]. These results suggest that adding EO alone had some positive effects on carcass characteristics, which may be due to the improvement in growth performance.

However, there was only a small amount of research on EO's effect on carcass characteristics, and only two research were conducted in the US. Therefore, more experiments are needed to determine the effect of including EO in the diets of grow-finish pigs.

Table A.4. Studies on the effects of dietary essential oils (EO) with or without acids on carcass characteristics.

Author	Country	Additive	Inclusion, %	Sig.[1]	Difference, %[1]			
					Yield	BF	percentage lean	LMA/LD
Essential oils								
Onibala et al. (2001)	Indonesia	Oregano EO	0.0025	Yield, BF, percentage lean	3.5	-7.5	2.4	n/a
		Thyme EO	0.0025	Yield, BF, percentage lean	3.8	-7.8	2.6	n/a
		Garlic EO	0.0025	Yield, BF, percentage lean	3.3	-7.7	2.5	n/a
Simitzis et al. (2010)	Greece	Oregano EO	0.025	ns	-0.6	4.1	n/a	n/a
			0.05	ns	0.1	-3.2	n/a	n/a
			0.1	ns	0.5	1.8	n/a	n/a
Yan et al. (2010)	South Korea	Thyme, rosemary, and oregano EO	0.01	LMA	n/a	n/a	n/a	12.3
Zhou et al. (2016)	China	Eucommia ulmoides oliver leaf polyphenolic extract	0.08	ns	0.8	-9.9	-2.5	-6.3
Zou et al. (2016)	China	Oregano EO	0.0025	Yield	8.2	-0.5	n/a	n/a
Li et al. (2017)	South Korea	Cinnamon, oregano, clove, thyme, and rosemary EO	0.05	LMA	n/a	n/a	n/a	5.4
			0.05	LMA	n/a	n/a	n/a	3.7
Soto et al. (2017)	USA	Caraway, garlic, thyme, and cinnamon	0.020	ns	0.3	6.3	-0.4	0.8
		Oregano, citrus, and anise	0.013	ns	0.0	3.1	0.0	1.2
		Caraway, garlic, thyme, cinnamon, oregano, citrus, and anise	0.033	ns	0.1	3.1	0.2	2.0
Cheng et al. (2018)	China	Oregano EO	0.025	ns	-0.8	-14.2	2.8	0.0
Lowell et al. (2018)	USA	Oregano EO	0.025	Yield	-0.8	-3.9	0.7	-0.1

Huang et al. (2021)	China	Eucalyptus, oregano, thyme, lemon, garlic EO	0.02	ns	0.3	-1.4	n/a	-0.6
Essential oils and Acidifier Blends								
Cho et al. (2014)	South Korea	Citric acids, sorbic acid, and EOs (thymol and vanillin)	0.025 0.05	ns[2]	n/a n/a	n/a n/a	n/a n/a	-2.7 -2.4
Walia et al. (2017)	Ireland	Formic acid, citric acid, and EOs (citrus fruit extract, cinnamon, oregano, thyme, and capsicum)	0.4	Yield, BF[3], percentage lean, LMA	-1.1	-7.0	2.0	4.0
Oh et al. (2019)	South Korea	Citric acids, sorbic acid, and EOs (thymol and vanillin)	0.1/0.025[4] 0.2/0.05[4]	percentage lean[2,3]	n/a n/a	4.2 4.2	0.5 2.6	0.1 1.5

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 \leq P < 0.10$.

[4]For the low inclusion treatment, feed additive was added at 0.1% in nursery phase and 0.025% in grow-finish phase. For the high inclusion treatment, feed additive was added at 0.2% in nursery phase and 0.05% in grow-finish phase.

3. Direct-Fed Microbials (DFM)

There were 48 research articles for DFM with 79 comparisons from 14 countries during the grow-finish or finishing period which met the requirements for inclusion. Of these, 73 comparisons reported growth performance data, and 33 comparisons reported carcass data. Most strains of DFM used in the studies were *Bacillus spp.*, *Lactobacillus spp.*, and *Enterococcus faecium.* A DFM additive could contain a single or several strains of microbials. In addition, comparisons were also included when yeast (*Saccharomyces cerevisiae*) was added with other microbials as a blended DFM product. The effect of the single addition of yeast in diets was discussed in the yeast section.

3.1. Growth Performance - DFM

Average daily gain significantly increased ($P \leq 0.05$) in 25 comparisons (average of 6.3%), tended to increase ($0.05 < P \leq 0.10$) in 2 comparisons (average of 3.9%), and significantly decreased ($P \leq 0.05$) in 1 comparison (5.8%) compared to control pigs (Table A.5). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (43 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 30 comparisons (average of 3.6%) and numerically decreased ($P > 0.10$) in 13 comparisons (average of 2.3%) compared to control pigs. in pigs fed DFM. Feed efficiency significantly increased ($P \leq 0.05$) in 18 comparisons (average of 6.1%) and tended to increase ($0.05 < P \leq 0.10$) in 3 comparisons (average of 3%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (45 comparisons). Of these, G:F was

numerically increased ($P > 0.10$) in 32 comparisons (average of 3.9%) and numerically decreased ($P > 0.10$) in 11 comparisons (average of 2.2%) compared to control pigs. Overall, the results suggest that DFM positively affected ADG and G:F (80% of all the comparisons). Moreover, DFM showed positive statistical improvement ($P < 0.10$) in 38 and 32% of all the comparisons for ADG and G:F, respectively. Similarly, Zimmermann et al. [50] conducted a meta-analysis and found probiotics significantly improved ADG and G:F of weaned piglets and finishing pigs. There were insufficient data to support whether different types of basal diets affected the response to DFM for ADG and G:F in grow-finish pigs. The effect of strain and inclusion level of DFM cannot be discussed because most studies used a blend of several microbials with varying concentrations. In summary, DFM has the potential to improve growth performance (3.3% improvement for ADG and G:F) of grow-finish pigs. However, there were relatively fewer US-based studies for DFM; therefore, the effects of DFM in US-based conditions may not be the same as what we discussed in this section.

Table A.5. Studies on the effects of DFM on growth performance.

Author	Country	DFM[4]	Inclusion, %	Sig.[1]	Difference, %[1]	
					ADG	G:F
Pollmann et al. (1980)	USA	*L. acidophilus*	0.05	ns	-1.2	-0.9
		Streptococcus faeciurn	0.05	ns	-1.2	-0.9
Harper et al. (1983)	USA	*L. acidophilus*	0.1/0.05	ADG	-5.8	-3.0
			0.05	ns	1.3	-1.4
Kim et al. (1998)	USA	*L. acidophilus*	0.05	ns	2.2	-0.4
Kyriakis et al. (2003)	Greece	*B. toyoi*	$1.0/0.5/0.2\times10^9$ spores/kg	ADG	4.5	n/a
			$1.0/0.5/0.2\times10^9$ spores/kg	ADG	8.3	n/a
Alexopoulos et al. (2004)	Greece	*B. licheniformis and B. subtilis*	0.04/0.02	ADG, G:F	2.2	4.5
			0.04/0.04	ADG, G:F	3.6	5.7
			0.04/0.06	ADG, G:F	3.6	5.3
Rekiel et al. (2005)	Poland	*Pediococcus acidilactici*	0.01	ns	-1.9	-1.9
Jukna et al. (2005)	Lithuania	*Saccharamyce cerevisiae, L. casei, L. acidophilus, Streptococcus faecium, B. subtilis*	0.20	ns	20.3	n/a
Shon et al. (2005)	South Korea	*L. reuteri and L. salivarius complex*	0.2	ns	3.2	1.4
Chen et al. (2006)	South Korea	*B. subtilis, B. coagulans, and L. acidophilus*	0.1	ns	5.3	3.7
			0.2	ADG	11.4	5.1
Chen et al. (2006)	South Korea	*Enterococcus faecium SF68*	0.1	ns[2]	4.9	2.0
			0.2		4.1	4.0
Davis et al. (2008)	USA	*B. lichenformis and B. subtilis*	0.05	G:F	0.6	3.0
Ko et al. (2008)	South Korea	*L. acidophilus, L. plantarum, B. subtilis, B. coagulans, and Saccharomyces cerevisiae*	0.5	ns	4.6	7.7
Ko and Yang (2008)	South Korea	*L. acidophilus, L. plantarum, B. subtilis, B. coagulans, and Saccharomyces cerevisiae*	0.1	ns	7.5	0.9
			0.5	ns	6.5	2.9
			1.0	ns	4.3	-1.4
Černauskienė et al. (2010), Exp. 1	Lithuania	*Enterococcus faecium*	10^{10} cfu/kg	ADG	3.1	-0.6

Černauskienė et al. (2010), Exp. 2	Lithuania	*Enterococcus faecium*	10^{10} cfu/kg	ns	1.5	3.0
Meng et al. (2010)	South Korea	*B. subtilis endospores and Clostridium butyricum*	0.2	ADG, G:F	7.5	7.9
Giang et al. (2011)	Vietnam	*B. subtilis*	0.3	ns	1.3	1.8
		B. subtilis and Saccharomyces boulardi	0.3	ns	2.6	2.9
		B., Saccharomyces boulardi, Enterococcus faecium, L. acidophilus, Pediococcus pentosaceus, and L. fermentum	0.3	ADG	5.2	5.3
Nitikanchana et al. (2011)	USA	*B. species*	0.2×10^9 cfu/g	ns[2]	-2.3	0.8
			2×10^9 cfu/g		-1.4	0.4
Hossain et al. (2012)	South Korea	*L. acidophilus, L. plantarum, B. subtilis, B. coagulans, and Saccharomyces cerevisiae*	0.5	ADG	7.9	6.0
Cui et al. (2013)	China	*B. subtilis*	2.0	ADG, G:F	3.6	2.4
Kerr et al. (2013)	USA	*Pediococcus acidilactici*	0.011	ns	0.8	-1.5
		B. licheniformis and B. subtilis	0.05	ns	-1.1	-5.4
Liu et al. (2013)	China	*Yeasts, lactic acid-producing bacteria, and B. subtilis*	1.0	ns	3.2	2.9
Balasubramanian et al. (2016)	South Korea	*B. coagulans, B. licheniformis, B. subtilis, and Clostridium butyricum*	0.01	ADG[2],	2.7	4.9
			0.02	G:F[2]	3.2	5.2
Dowarah et al. (2016)	India	*L. acidophilus NCDC-15*	0.02	ADG, G:F	11.7	9.4
		Pediococcus acidilactici FT28	0.02	ADG, G:F	14.9	9.8
Giannenas et al. (2016)	Greece	*Enterococcus faecium*	0.0035	ns	3.0	6.8
Jørgensen et al. (2016)	Denmark	*B. licheniformis and B. subtilis*	0.04	ADG, G:F	3.3	1.9
Sarker et al. (2016)	South Korea	*L. acidophilus, L. plantarum, B. subtilis, B. coagulans, and Saccharomyces cerevisiae*	0.2	ns	-6.2	-7.2
			0.4	ns	-0.5	3.9
			0.8	ns	2.1	13.1
Nguyen et al. (2017)	South Korea	*Enterococcus faecium*	0.01	ADG, G:F	3.9	3.1
Tufarelli et al. (2017)	Italy	*Streptococcus thermophilus, Bifidobacterium animalis ssp. Lactis, L. acidophilus, L. helveticus, L. paracasei, L. plantarum, and L. brevis.*	100 mg/kg BW	ADG3	3.0	n/a
Balasubramanian et al. (2018)	South Korea		0.01	ADG, G:F	6.0	8.4

		B. coagulans, B. licheniformis, B. subtilis, and Clostridium butyricum	0.02	ADG, G:F	7.4	9.3
Bučko et al. (2018)	Slovak	*L. plantarum*	3g/day	ns	-1.2	0.4
Nguyen Thi (2018)	Vietnam	*B. subtilis, L. spp., Saccharomyces cerevisiae*	0.2	ADG	4.7	3.3
Samolińska et al. (2018)	Poland	*L. lactis, Carnobacterium divergens, L. casei, L. plantarum, and Saccharomyces cerevisiae*	0.05[5]	ns	2.2	2.2
			0.05[5]	ns	3.1	3.5
			0.05[5]	ns	2.5	3.0
Shi et al. (2018)	China	*B. subtilis and Devosia sp.*	0.2	ns	-3.2	10.9
			0.2	ADG	15.3	5.1
Lan and Kim (2019)	South Korea	*B. licheniformis and B. subtilis*	0.02	ns[2]	1.8	0.0
			0.04		2.0	0.9
			0.08		5.4	1.2
Wang and Kim (2019)	South Korea	*B. subtilis and P. farinosa*	0.1	ADG[2], G:F[2,3]	1.7	2.0
			0.2		3.8	4.0
Peet-Schwering et al. (2020)	Netherlands	*B. amyloliquefaciens and B. subtilis*	0.04	G:F	1.4	0.5
Reszka et al. (2020)	Poland	*EM Carbon Bokash*	0.5/0.3	ns	1.4	0.8
Rybarczyk et al. (2020)	Poland	*Saccharomyces cerevisiae, L. casei, and L. plantarum*	0.30	ns	-5.9	n/a
			0.50	ns	-2.4	n/a
Frimpong et al. (2021)	Ghana	*L. sp., B. sp., and Saccharomyces cerevisiae*	0.1	ns	n/a	9.0
		L. sp., B. sp., Saccharomyces cerevisiae, and Paenibacillus polymyxa	0.15	ns	n/a	4.1
Grela et al. (2021)	Poland	*Lactococcus lactis, Carnobacterium divergens S1, L. casei, L. plantarum, and Sacharomyces cerevisiae*	0.1	ADG, G:F[3]	2.5	3.0
Kwak et al. (2021)	South Korea	*L. plantarum, L. fermentum, L. salivarius, Leuconostoc paramesenteroides, and B. subtilis, and B. licheniformis*	0.2	ADG[3], G:F	4.8	8.6
Pomorska-Mól et al. (2021)	Poland	*Leuconostoc mesenteroides, L. casei, L. plantarum, Pediococcus pentosaceus.*	4×10^{12} cfu/kg	ns	3.7	n/a
Rybarczyk et al. (2021)	Poland	*B. licheniformis and B. subtilis*	0.04	ADG, G:F	14.6	7.7
Shen et al. (2021)	China	*B. subtilis*	5×10^{9} cfu/kg	ns	0.8	6.7
		biodegradable *B. subtilis*	5×10^{9} cfu/kg	G:F	3.6	13.0
Tutida et al. (2021)	Brazil	*B. spp., B. bifidum, E. faecium, L. acidophilus*	0.05	ns	-1.4	0.0

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]*Bacillus spp.* is abbreviated as *B.*, and *Lactobacillus spp.* is abbreviated as *L.*

[5]The basal diets in the middle and bottom comparison contained long-chain inulin and Jerusalem artichoke, respectively, while the top comparison did not.

3.2. Carcass Characteristics - DFM

Back-fat significantly increased ($P \leq 0.05$) in 1 comparison (16.8%), significantly decreased ($P \leq 0.05$) in 2 comparisons (average of 13.1%) and tended to decrease ($0.05 < P \leq 0.10$) in 3 comparisons (average of 2.9%) compared to control pigs (Table A.6). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (15 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 6 comparisons (average of 7.1%) and numerically decreased ($P > 0.10$) in 9 comparisons (average of 6.3%) compared to control pigs. Percentage lean tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (1.8%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (12 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 9 comparisons (average of 1.8%) and numerically decreased ($P > 0.10$) in 3 comparisons (average of 1.8%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 1 comparison (average of 10.9%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (18 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 14 comparisons (average of 2%) and numerically decreased ($P > 0.10$) in 3 comparisons (average of 3.4%) compared to control pigs. The small effects and lack of statistical differences of DFM on carcass characteristics may suggest that the mechanisms of DFM do not directly affect pigs' protein and lipid metabolism. Even though

DFM has beneficial effects on growth performance, the improvement in growth did not equally improve BF, percentage lean, and LMA/LD to the same extent.

Table A.6. Studies on the effects of DFM on carcass characteristics.

Author	Country	DFM[4]	Inclusion, %	Sig.[1]	Difference, %[1]			
					Yield	BF	percentage lean	LMA/LD
Kim et al. (1998)	USA	*L. acidophilus*	0.05	ns	0.8	-5.6	1.5	n/a
Jukna et al. (2005)	Lithuania	*Saccharamyce cerevisiae, L. casei, L. acidophilus, Streptococcus faecium, B. subtilis*	0.20	ns	2.7	n/a	n/a	n/a
Rekiel et al. (2005)	Poland	*Pediococcus acidilactici*	0.01	ns	0.3	0.4	2.4	2.2
Černauskienė et al. (2010), Exp. 1	Lithuania	*Enterococcus faecium*	10^{10} cfu/kg	ns	-0.3	n/a	-2.0	n/a
Černauskienė et al. (2010), Exp. 2	Lithuania	*Enterococcus faecium*	10^{10} cfu/kg	ns	0.1	n/a	n/a	n/a
Meng et al. (2010)	South Korea	*B. subtilis endospores and Clostridium butyricum*	0.2	ns	n/a	n/a	n/a	4.3
Nitikanchana et al. (2011)	USA	*B. species*	0.2×10^9 cfu/g	BF[2,3]	0.5	-4.2	0.7	0.0
			2×10^9 cfu/g		0.9	-1.4	0.5	1.1
Hossain et al. (2012)	South Korea	*L. acidophilus, L. plantarum, B. subtilis, B. coagulans, and Saccharomyces cerevisiae*	0.5	ns	n/a	20.3	n/a	n/a
Cui et al. (2013)	China	*B. subtilis*	2.0	BF, LMA	2.0	16.8	n/a	10.9
Balasubramanian et al. (2016)	South Korea	*B. coagulans, B. licheniformis, B. subtilis, and Clostridium butyricum*	0.01	ns[2]	n/a	4.5	0.9	1.2
			0.02		n/a	-5.1	1.5	2.4
Sarker et al. (2016)	South Korea	*L. acidophilus, L. plantarum, B. subtilis, B. coagulans, and Saccharomyces cerevisiae*	0.2	ns	n/a	-10.9	n/a	n/a
			0.4	ns	n/a	-4.2	n/a	n/a
			0.8	ns	n/a	-9.1	n/a	n/a
Nguyen et al. (2017)	South Korea	*Enterococcus faecium*	0.01	ns	n/a	n/a	n/a	0.5
Balasubramanian et al. (2018)	South Korea	*B. coagulans, B. licheniformis, B. subtilis, and Clostridium butyricum*	0.01	ns	n/a	-2.2	n/a	0.1
			0.02	BF	n/a	-8.2	n/a	2.8
Bučko et al. (2018)	Slovak	*L. plantarum*	3g/day	BF	n/a	-18.1	3.6	1.2

Nguyen Thi (2018)	Vietnam	*B. subtilis, L. spp., Saccharomyces cerevisiae*	0.2	ns	-0.8	-1.0	n/a	2.9
Runjun et al. (2018)	India	*P. acidilactici*	2×10^9 cfu/g	ns	0.6	-10.7	3.1	n/a
		L. acidophilus	2×10^9 cfu/g	ns	-0.5	-7.9	2.1	n/a
Reszka et al. (2020)	Poland	EM Carbon Bokash	0.5/0.3	ns	n/a	n/a	n/a	5.0
			0.5/0.3	ns	n/a	n/a	n/a	-1.5
			0.5/0.3	ns	n/a	n/a	n/a	0.6
Rybarczyk et al. (2020)	Poland	*Saccharomyces cerevisiae, L. casei, and L. plantarum*	0.30	ns	n/a	8.1	-2.0	-5.8
			0.50	ns	n/a	6.3	-1.3	-2.9
Grela et al. (2021)	Poland	*Lactococcus lactis, Carnobacterium divergens S1, L. casei, L. plantarum, and Sacharomyces cerevisiae*	0.1	BF[3], percentage lean[3]	-0.5	-3.0	1.8	1.9
Rybarczyk et al. (2021)	Poland	*B. licheniformis and B. subtilis*	0.04	ns	0.9	n/a	n/a	n/a
Tian et al. (2021)	China	*L. reuteri*	5×10^{10} cfu/kg	ns	2.2	3.1	n/a	1.9

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.
[2]Polynomial contrasts were used for statistical analysis.
[3]Significant level at $0.05 < P \leq 0.10$.
[4]*Bacillus spp.* is abbreviated as *B.*, and *Lactobacillus spp.* is abbreviated as *L.*

4. Yeasts – Yeast Culture and Yeast-Derived Ingredients

There were 22 research articles for yeasts with 36 comparisons from 12 countries during the grow-finish or finishing period which met the requirements for inclusion. Of these, 36 comparisons reported growth performance data, and 24 comparisons reported carcass data. Yeast was included in the diets as yeast culture, hydrolysate yeast culture, or mannan oligosaccharide (**MOS**). Yeast products were derived from *Saccharomyces cerevisiae* (yeast) and *Phaffia rhodozyma* (red yeast) yeast strains. Because of the lack of studies for individual yeast products, the effects of yeast culture and yeast-derived ingredients were combined and discussed for growth performance and carcass characteristics.

4.1. Growth Performance - Yeasts

Average daily gain significantly increased ($P \leq 0.05$) in 9 comparisons (average of 5.6%) compared to control pigs (Table A.7). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (27 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 16 comparisons (average of 3.2%) and numerically decreased ($P > 0.10$) in 11 comparisons (average of 4.1%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 10 comparisons (average of 7.8%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (23 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 12 comparisons (average of 3.9%) and numerically decreased ($P > 0.10$) in 10 comparisons (average of 3.6%) compared to control pigs. There were not enough data to support whether different

basal diets affected the response of yeasts on ADG and G:F. Moreover, there were insufficient comparisons or information to determine the effect of different concentrations of active yeast ingredients on ADG and G:F. Overall, the results suggest that yeasts positively affected ADG and G:F (69 and 67% of all the comparisons, respectively), with 25 and 30% of all the comparisons being significant ($P \leq 0.05$). In summary, yeasts can be a potential feed additive with relatively large magnitude on improving the growth performance of grow-finish pigs, especially for G:F.

Table A.7. Studies on the effects of yeasts and yeast-derived ingredients on growth performance.

Author	Country	Yeast form[6]	Inclusion, %	Sig.[1]	Difference, %[1]	
					ADG	G:F
Barber et al. (1971)	UK	Yeast culture	(7.1 and 3.1)/(3.6 and 1.6)[4]	ADG	2.9	n/a
Bowman and Veum (1973)	USA	Yeast culture	2.00[5]	ns	-5.3	0.0
			2.00[5]	ns	2.9	3.3
Burnett and Neil (1977), Exp. 1	UK	Yeast culture	0.05	ns	-0.6	-0.9
Burnett and Neil (1977), Exp. 2	UK	Yeast culture	0.05	ns	0.6	0.0
Bae et al. (1999)	South Korea	MOS	0.10	ns	1.3	4.7
Davis et al. (2002)	USA	MOS	0.2	ns	1.2	-1.3
Campbell et al. (2006)	Ireland	MOS	0.15	ns	-5.4	-7.0
Reynoso-González et al. (2010), Exp. 1	Mexico	Yeast culture	0.75	ns	-7.0	-2.6
			1.5	ns	-3.5	-3.2
Reynoso-González et al. (2010), Exp. 2	Mexico	Yeast culture	0.75[5]	ns	4.8	4.9
			0.75[5]	ns	-2.2	-6.1
Ha et al. (2012)	South Korea	Yeast culture	2.0	ns	-1.4	n/a
Kerr et al. (2013)	USA	Yeast culture	0.1	ns	-13.7	-11.7
Wenner et al. (2013)	USA	MOS	0.2/0.1/0.055	ns	0.8	1.6
Edwards et al. (2014)	Australia	MOS	0.04/0.025	ns	3.6	3.9
Lei and Kim (2014)	South Korea	Yeast culture[6]	0.1	G:F[2]	3.6	4.6
			0.2		2.4	5.2
Giannenas et al. (2016)	Greece	MOS	0.1	ns	3.4	9.1
Szakacs et al. (2016)	Romania	Yeast extract	0.03	ns	4.9	10.4
			0.03	ns	1.6	-2.5
Gong et al. (2018)	China	Yeast culture	0.3	ADG	8.4	5.2
Zhang et al. (2019)	South Korea	Hydrolysate yeast culture	0.05	ADG[2], G:F[2]	2.6	3.8
			0.10		3.7	0.8
			0.50		3.9	4.8
			1.00		7.0	5.0
Bo et al. (2020)	Vietnam	Yeast extract	2.00	G:F	6.0	13.2
			4.00	G:F	9.7	17.7

			6.00	G:F	10.3	16.8
Dávila-Ramírez et al. (2020)	Mexico	Yeast culture	0.2	ADG	5.4	2.0
			0.3	ADG	6.1	-0.5
He et al. (2021)	China	Yeast culture	2.0	ns	-1.6	1.5
Mayorga et al. (2021)	USA	Yeast culture	0.025	ns	3.3	n/a
Namted et al. (2021)	Thailand	Hydrolysate yeast culture	0.5	G:F	-1.6	6.6
			1.0	ns	-2.3	0.4
Tutida et al. (2021)	Brazil	MOS	0.04/0.02	ns	0.8	-0.4

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]Inclusion levels of sequential phases.

[5]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[6]Yeast culture and yeast-derived ingredients (MOS) were produced from strains of *Saccharomyces cerevisiae*, except the yeast culture used in Lei and Kim (2014). Yeast culture used in Lei and Kim (2014) was derived from *Phaffia rhodozyma*.

4.2. Carcass Characteristics - Yeasts

All 21 comparisons found no evidence of difference ($P > 0.10$) in BF. Of these, BF was numerically increased ($P > 0.10$) in 12 comparisons (average of 4.1%) and numerically decreased ($P > 0.10$) in 8 comparisons (average of 14.4%) compared to control pigs (Table A.8). Percentage lean tended to increase ($0.05 < P \leq 0.10$) in 3 comparisons (average of 0.8%) and tended to decrease ($0.05 < P \leq 0.10$) in 1 comparison (1.2%) compared to control pigs. Half of the studies found no evidence of difference ($P > 0.10$) in percentage lean (4 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 2 comparisons (average of 4.9%) and numerically decreased ($P > 0.10$) in 2 comparisons (average of 1.3%) compared to control pigs.. All the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD. Of these, LMA/LD was numerically increased ($P > 0.10$) in 10 comparisons (average of 3.6%) and numerically decreased ($P > 0.10$) in 7 comparisons (average of 1.9%) compared to control pigs.

Table A.8. Studies on the effects of yeasts and yeast-derived ingredients on carcass characteristics.

Author	Country	Yeast form[6]	Inclusion, %	Sig.[1]	Difference, %[1]			
					Yield	BF	percentage lean	LMA/LD
Barber et al. (1971)	UK	Yeast culture	(7.1 and 3.1)/(3.6 and 1.6)[4]	ns	-0.9	0.5	n/a	-0.6
Bowman and Veum (1973)	USA	Yeast culture	2.00[5]	ns	n/a	7.1	-0.9	-3.2
			2.00[5]	ns	n/a	-2.8	-1.7	0.7
Burnett and Neil (1977), Exp. 2	UK	Yeast culture	0.05	ns	0.9	2.5	n/a	n/a
Campbell et al. (2006)	Ireland	MOS	0.15	ns	-0.6	n/a	n/a	n/a
Reynoso-González et al. (2010), Exp. 1	Mexico	Yeast culture	0.75	ns	-2.3	-12.4	n/a	-2.4
			1.5	ns	0.0	-19.4	n/a	6.9
Reynoso-González et al. (2010), Exp. 2	Mexico	Yeast culture	0.75[5]	ns	1.1	-10.6	n/a	0.9
			0.75[5]	ns	-0.8	8.0	n/a	-0.3
Ha et al. (2012)	South Korea	Yeast culture	2.0	ns	n/a	0.0	n/a	n/a
Wenner et al. (2013)	USA	MOS	0.2/0.1/0.055	ns	n/a	-2.6	n/a	1.4
Edwards et al. (2014)	Australia	MOS	0.04/0.025	Yield	2.2	2.7	n/a	n/a
Lei and Kim (2014)	South Korea	Yeast culture[6]	0.1	ns[2]	n/a	n/a	n/a	2.5
			0.2		n/a	n/a	n/a	0.8
Zhang et al. (2019)	South Korea	Hydrolysate yeast culture	0.05	percentage lean[2,3]	n/a	0.8	-1.2	n/a
			0.1		n/a	3.3	0.6	n/a
			0.5		n/a	3.5	1.4	n/a
			1.0		n/a	4.5	0.4	n/a
Bo et al. (2020)	Vietnam	Yeast extract	2.00	ns	n/a	0.0	n/a	1.6
			4.00	ns	n/a	1.3	n/a	0.5
			6.00	ns	n/a	4.0	n/a	-0.3
Dávila-Ramírez et al. (2020)	Mexico	Yeast culture	0.2	ns	0.0	-24.6	n/a	4.7
			0.3	ns	0.5	11.2	n/a	16.6
Namted et al. (2021)	Thailand	Hydrolysate yeast culture	0.5	ns	-0.8	-30.7	6.6	-1.9
			1.0	ns	-0.4	-12.2	3.2	-4.3

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]Inclusion levels of sequential phases.

[5]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[6]Yeast culture and yeast-derived ingredients (MOS) were produced from strains of *Saccharomyces cerevisiae*, except the yeast culture used in Lei and Kim (2014). Yeast culture used in Lei and Kim (2014) was derived from *Phaffia rhodozyma*.

5. Copper (Cu)

There were 55 research articles for Cu with 157 comparisons from 11 countries during the grow-finish or finishing period with added dietary levels of 50 to 300 mg/kg with most studies ranged between 120 to 250 mg/kg. Of these, 155 comparisons reported growth performance data and 83 comparisons reported carcass data. The Cu sources used in the studies were in inorganic [$CuSO_4$, Cu_2O, CuO, Tribasic Cu chloride (**TBCC**), CuS] or organic form (Cu-AAs).

5.1. Growth Performance - Cu

Average daily gain significantly increased ($P \leq 0.05$) in 30 comparisons (average of 6.2%), tended to increase ($0.05 < P \leq 0.10$) in 3 comparisons (average of 4.1%), and significantly decreased ($P \leq 0.05$) in 1 comparison (0.1%) compared to control pig (Table A.9). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (121 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 81 comparisons (average of 3.8%) and numerically decreased ($P > 0.10$) in 33 comparisons (average of 3.4%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 30 comparisons (average of 5.1%), tended to increase ($0.05 < P \leq 0.10$) in 3 comparisons (average of 1.0%), and significantly decreased ($P \leq 0.05$) in 2 comparisons (average of 3.7%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (114 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 71 comparisons (average of 3.1%) and numerically decreased ($P > 0.10$) in 37 comparisons (average of 2.7%) compared to

control pigs. Overall, the results suggest that Cu positively affected ADG and G:F (74 and 70 % of all the comparisons). Most studies used corn or barley as the major ingredient in basal diets. Copper supplementation in the barley diet had a greater percentage improvement in ADG (2.8%; 60 comparisons) and G:F (3.1%; 59 comparisons) than Cu supplementation in corn-based diets [ADG (2.0%; 89 comparisons) and G:F (0.8%; 84 comparisons)]. Most studies used Cu inclusion from 125 to 250 mg/kg added level (137 comparisons) and increasing the Cu level did not further improve the performance. In summary, the growth-promoting effects of Cu can potentially improve growth performance (2.5 and 1.8% improvement for ADG and G:F).

Table A.9. Studies on the effects of Cu on growth performance.

Author	Country	Cu	Inclusion, mg/kg	Sig.	Difference, % ADG	Difference, % G:F
Lucas and Calder (1957), Exp. 1	UK	$CuSO_4$	200	ns	3.9	0.7
Lucas and Calder (1957), Exp. 2	UK	$CuSO_4$	200	ns	6.5	7.1
King (1960)	UK	$CuSO_4$	0.10%	G:F	2.9	6.1
			0.10%	ADG, G:F	7.7	11.0
Wallace et al. (1960), Exp. 1	USA	$CuSO_4$	100	ns	11.1	-1.8
			150	ns	5.2	0.9
			200	ns	0.7	0.9
Wallace et al. (1960), Exp. 2	USA	$CuSO_4$	200[4]	ns	-3.8	-8.0
			200[4]	ns	3.3	4.5
Wallace et al. (1960), Exp. 3	USA	$CuSO_4$	100[4]	ns	0.0	17.6
			100[4]	ns	-6.5	0.3
Bellis (1961)	UK	$CuSO_4$	125	ns	3.9	3.3
			250	ADG, G:F	7.1	8.0
Lucas et al. (1961), Exp. 1	UK	$CuSO_4$	62	ns	-1.1	-1.4
			125	ns	1.1	0.6
			250	ns	4.5	0.6
Lucas et al. (1961), Exp. 2	UK	$CuSO_4$	62	ns	2.2	0.9
			125	ns	2.2	1.8
			250	ns	3.3	2.1
Barber et al. (1962)	UK	$CuSO_4$	250[4]	ADG, G:F	14.5	5.5
			250[4]	ADG	5.1	2.2
Braude et al. (1962)	UK	$CuSO_4$	250[4]	ADG, G:F	9.7	8.6
			250[4]	ADG, G:F	6.2	5.2
Lucas et al. (1962)	UK	$CuSO_4$	250	ns	2.6	-0.1
Gipp et al. (1967)	USA	CuO	150[4]	ns	-4.7	-2.3
			150[4]	ns	0.4	4.2
Barber et al. (1968), Exp. 1	UK	$CuSO_4$	250	ADG, G:F	11.1	9.0
Barber et al. (1968), Exp. 2	UK	$CuSO_4$	250	ns	7.1	3.9
Barber et al. (1968), Exp. 3	UK	$CuSO_4$	250	G:F	5.3	4.4
Hanrahan and O'Grady (1968)	Ireland	$CuSO_4$	250	ns	-12.2	-6.0
Boyazoglu and Barrett (1970)	South Africa	$CuSO_4$	150	ns	n/a	4.4
			300	ns	n/a	-0.8
Barber et al. (1971), Exp. 1	UK	$CuSO_4$	250[4]	G:F	4.5	5.3
			250[4]	G:F	-1.4	4.1
Barber et al. (1971), Exp. 2	UK	$CuSO_4$	250[4]	ADG, G:F	8.1	6.1
			250[4]	ns	-3.8	-1.3
Barber et al. (1971), Exp. 3	UK	$CuSO_4$	250	ADG, G:F	7.4	5.6
DeGoey et al. (1971)	USA	$CuSO_4$	250	ADG	15.2	1.9
Kline et al. (1971)	USA	$CuSO_4$	150	ADG[2]	7.2	-2.4
			200		-0.1	-7.8

			250		8.4	-0.5
Kline et al. (1972)	USA	$CuSO_4$	250[4]	ns	14.8	5.4
			250[4]	ns	-3.2	10.7
			250[4]	ns	5.5	-6.7
Braude and Ryder (1973)	UK	$CuSO_4$	150		3.1	3.6
			200	ADG[2], G:F[2]	4.4	3.9
			250		5.9	5.5
Elliot and Amer (1973), Exp. 1	Canada	$CuSO_4$	250	ns	-6.8	n/a
Elliot and Amer (1973), Exp. 2	Canada	$CuSO_4$	125	ns	-4.3	10.0
			150	ns	0.0	0.3
			175	ns	1.8	1.9
			200	ns	1.8	10.0
			225	ns	-3.7	1.9
			250	ns	-10.2	1.3
Gipp et al. (1973), Exp. 1	USA	$CuSO_4$	250	ns	4.1	3.3
Gipp et al. (1973), Exp. 2	USA	$CuSO_4$	250	ns	-1.3	-3.3
Gipp et al. (1973), Exp. 3	USA	$CuSO_4$	250	ns	-4.0	-0.7
Kline et al. (1973), Exp. 1	USA	$CuSO_4$	250	ADG, G:F	8.9	6.7
Kline et al. (1973), Exp. 2	USA	$CuSO_4$	250	ns	0.4	-2.9
Kline et al. (1973), Exp. 3	USA	$CuSO_4$	250	ns	-5.5	9.3
NCR-42 Committee on Swine Nutrition (1974), Exp. 1	USA	$CuSO_4$	250	ns	1.8	0.1
NCR-42 Committee on Swine Nutrition (1974), Exp. 2	USA	$CuSO_4$	125.5	ns	2.1	0.3
			187.5	ns	2.3	-0.3
			250	ns	3.5	1.5
Bellis (1975)	UK	$CuSO_4$	175[4]	ns	-1.5	0.0
			175[4]	ADG, G:F	3.1	2.8
Castell et al. (1975), Exp. 1	Canada	$CuSO_4$	125[5]	ns	4.8	-1.5
			200[5]	ns	8.7	4.1
			125[5]	ns	4.3	4.2
			200[5]	ns	6.3	3.5
Castell et al. (1975), Exp. 2	Canada	$CuSO_4$	125[5]	ns	2.0	2.2
			200[5]	ns	1.7	0.9
			125[5]	ns	2.8	5.5
			200[5]	ns	2.6	5.2
Castell et al. (1975), Exp. 3	Canada	$CuSO_4$	125	ns	-0.4	-3.3
			200	ns	0.9	-3.0
Castell et al. (1975), Exp. 4	Canada	$CuSO_4$	125	ns	2.0	3.3
			200	ns	-2.0	2.9
Castell et al. (1975), Exp. 5	Canada	$CuSO_4$	125	ns	3.3	2.1
			200	G:F	3.1	4.3
Hansen and Bresson (1975)	Denmark	$CuSO_4$	125	ADG, G:F	4.9	5.2
			200	ADG	3.9	3.2
Omole et al. (1976)	Nigeria	$CuSO_4$	125	ns	9.3	5.5
			200	G:F	14.8	8.5

Barber et al. (1978)	UK	NA	250	ADG, G:F	2.0	2.9
Cromwell et al. (1978), Exp. 1	USA	$CuSO_4$	125	ns	4.5	0.3
			188	ns	2.8	-2.2
			250	ns	14.0	2.0
Cromwell et al. (1978), Exp. 2	USA	$CuSO_4$	125	G:F	0.4	2.3
			250	G:F	1.3	3.5
Cromwell et al. (1978), Exp. 3	USA	$CuSO_4$	250	ns	2.8	2.5
		CuS	250	ns	-2.7	2.2
Pond et al. (1978)	USA	$CuSO_4$	200	ns	0.0	-3.2
Eisemann et al. (1979)	USA	$CuSO_4$	120	ns	-6.6	-2.0
Prince et al. (1979), Exp. 1	USA	$CuSO_4$	250	ns	1.8	1.5
Prince et al. (1979), Exp. 2	USA	$CuSO_4$	250	ns	5.3	5.4
Barber et al. (1981), Exp. 1	UK	$CuSO_4$	250	ADG, G:F	4.1	3.7
Barber et al. (1981), Exp. 2	UK	$CuSO_4$	250	ADG, G:F	2.6	2.5
Ribeiro de Lima et al. (1981), Exp. 1	USA	$CuSO_4$	250[4]	ns	10.0	1.7
			250[4]	ns	-4.6	0.0
			250[4]	ns	-3.7	-1.4
Ribeiro de Lima et al. (1981), Exp. 2	USA	$CuSO_4$	250	ns	0.8	-4.6
Ribeiro de Lima et al. (1981), Exp. 3	USA	$CuSO_4$	250	ns	0.0	1.5
Braude and Hosking (1982)	UK	$CuSO_4$	125	ADG, G:F	4.4	4.8
			200	ADG, G:F	3.1	2.8
			200/125	ADG, G:F	3.3	3.4
			250/125	ADG, G:F	4.9	4.8
Bradley et al. (1983)	USA	$CuSO_4$	52.5	ns	0.0	n/a
			112.5	ns	-1.8	n/a
			232.5	ns	-1.8	n/a
Prince et al. (1984), Exp. 1	USA	$CuSO_4$	250	ns	0.1	1.4
Prince et al. (1984), Exp. 2	USA	$CuSO_4$	250	ADG[3]	3.0	1.6
Southern and Stewart (1984), Exp. 1	USA	$CuSO_4$	250	ns	3.8	n/a
Southern and Stewart (1984), Exp. 2	USA	$CuSO_4$	250	ns	0.0	n/a
Rowan and Lawrence (1986)	UK	NA	183	ns	-0.1	-0.7
Astrup and Matre (1987)	Norway	$CuSO_4$	63	ns	1.1	6.3
			125	ns	4.8	5.3
			250	ns	3.5	4.6
Lüdke and Schöne (1988), Exp.1	Germany	$CuSO_4$	250	ns	10.7	2.1
Lüdke and Schöne (1988), Exp.2	Germany	$CuSO_4$	250	ns	5.7	2.5
Schöne et al. (1988)	Germany	$CuSO_4$	250	ns	14.2	5.2
Ward et al. (1991)	USA	$CuSO_4$	250	ns	2.5	-5.5

Myer et al. (1992)	USA	$CuSO_4$	250	ns	-1.1	-1.1
Southern et al. (1993)	USA	NA	250	ns	-1.1	0.0
Apgar and Kornegay (1996)	USA	$CuSO_4$	200	ns	-2.8	n/a
		Cu-Lys	200	ns	11.1	n/a
Lauridsen et al. (1999)	Denmark	$CuSO_4$	175	ns	0.3	-5.0
Davis et al. (2002)	USA	$CuSO_4$	175/125	ADG, G:F	6.6	3.6
Hernández et al. (2009)	Australia	Cu-AA	50[4]	G:F	-1.1	-5.4
			50[4]	ns	-3.2	0.4
Coble et al. (2014)	USA	$CuSO_4$	50	G:F	2.0	-1.9
			125	ns	1.5	-1.9
		Cu-AA	50	ns	2.0	-0.4
Feldpausch et al. (2016)	USA	$CuSO_4$	125[4]	ns	0.5	1.3
			125[4]	ns	-0.5	-1.3
Coble et al. (2017)	USA	$CuSO_4$/TBCC	75	ADG[2]	3.9	-2.2
			150		3.9	-1.8
Coble et al. (2018)	USA	TBCC	150	ns	1.7	0.3
Coble et al. (2018), Exp. 1	USA	TBCC	150[4]	ADG[3], GF[3]	0.0	0.3
			150[4]	ADG[3], GF[3]	0.0	1.1
			150[4]	ADG[3], GF[3]	2.4	1.6
Coble et al. (2018), Exp. 2	USA	TBCC	150[6]	ns	0.0	0.3
			150[6]	ns	1.1	0.0
			150[6]	ns	2.2	1.8
			150[6]	ns	1.1	0.6
Carpenter et al. (2019)	USA	$CuSO_4$/Cu-AA	70	ns[2]	1.7	0.8
			100		2.3	1.1
			130		1.1	1.7
Seidu et al. (2020)	China	$CuSO_4$	125	ns	4.2	-1.1
			215	ADG	5.2	-6.2
Blavi et al. (2021)	USA	$CuSO_4$	125	ns	2.2	0.0
			250	ns	1.1	-0.5
		Cu_2O	125	ns	2.2	0.0
			250	ADG[3]	6.7	-2.9

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]The top two comparisons were the results of the barrows and the bottom two comparisons were the results of the gilts.

[6]The top two comparisons were the results of the feeding Cu in grow-finish phase and the bottom two comparisons were the results of feeding Cu in the finish phase. The basal diet Lys concentrations from the top to bottom comparisons were at 92.5, 100, 92.5, and 100% of the requirement.

5.2. Carcass Characteristics – Cu

Back-fat significantly decreased ($P \leq 0.05$) in 3 comparisons (average of 10.3%) and tended to decrease ($0.05 < P \leq 0.10$) in 1 comparison (5.4%) compared to control pigs (Table A.10). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (69 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 24 comparisons (average of 3.5%) and numerically decreased ($P > 0.10$) in 36 comparisons (average of 4.1%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in 2 comparisons (average of 1.1%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (23 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 16 comparisons (average of 2.8%) and numerically decreased ($P > 0.10$) in 7 comparisons (average of 1.1%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 5 comparisons (average of 4.4%) and significantly decreased ($P \leq 0.05$) in 1 comparison (7.5%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (56 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 43 comparisons (average of 3.4%) and numerically decreased ($P > 0.10$) in 11 comparisons (average of 1.4%) compared to control pigs.

Table A.10. Studies on the effects of Cu on carcass characteristics.

Author	Country	Form	Inclusion, mg/kg	Sig.	Difference, %			
					Yield	BF	percentage lean	LMA/LD
Lucas and Calder (1957), Exp. 1	UK	$CuSO_4$	200	ns	1.3	-7.5	n/a	1.5
Lucas and Calder (1957), Exp. 2	UK	$CuSO_4$	200	ns	-0.1	-9.1	n/a	2.7
Bellis (1961)	UK	$CuSO_4$	125	ns	0.5	n/a	n/a	n/a
			250	ns	0.1	n/a	n/a	n/a
Lucas et al. (1961), Exp. 1	UK	$CuSO_4$	62	ns	1.1	-4.8	n/a	1.4
			125	ns	1.8	0.0	n/a	-0.7
			250	ns	2.0	0.0	n/a	-1.4
Lucas et al. (1961), Exp. 2	UK	$CuSO_4$	62	ns	-0.3	0.0	n/a	5.4
			125	ns	0.4	3.8	n/a	2.5
			250	ns	0.7	3.8	n/a	5.0
Braude et al. (1962)	UK	$CuSO_4$	250[4]	ns	n/a	0.7	n/a	1.4
			250[4]	ns	n/a	1.4	n/a	3.9
Lucas et al. (1962)	UK	$CuSO_4$	250	ns	-0.1	4.4	n/a	5.0
Boyazoglu and Barrett (1970)	South Africa	$CuSO_4$	150	ns	0.0	-7.5	n/a	12.5
			300	ns	0.6	-10.0	n/a	9.5
Barber et al. (1971), Exp. 1	UK	$CuSO_4$	250[4]	ns	1.1	-1.2	n/a	n/a
			250[4]	ns	0.4	-17.0	n/a	n/a
Barber et al. (1971), Exp. 2	UK	$CuSO_4$	250[4]	ns	0.1	-4.0	n/a	n/a
			250[4]	ns	0.3	9.3	n/a	n/a
Barber et al. (1971), Exp. 3	UK	$CuSO_4$	250	ns	-0.5	-1.0	n/a	n/a
Braude and Ryder (1973)	UK	$CuSO_4$	150	ns[2]	0.5	1.9	n/a	1.9
			200		0.7	0.0	n/a	1.9
			250		0.4	0.0	n/a	3.4
Gipp et al. (1973), Exp. 2	USA	$CuSO_4$	250	LMA	n/a	-2.4	-1.3	-7.5
Gipp et al. (1973), Exp. 3	USA	$CuSO_4$	250	ns	n/a	-1.5	0.7	2.1

NCR-42 Committee on Swine Nutrition (1974), Exp. 1	USA	$CuSO_4$	250	ns	n/a	-10.2	n/a	4.3
Bellis (1975)	UK	$CuSO_4$	175	ns	0.1	-2.7	n/a	1.0
			175	ns	0.4	2.2	n/a	1.7
Castell et al. (1975), Exp. 1	Canada	$CuSO_4$	125[5]	ns	1.9	n/a	n/a	0.0
			200[5]	ns	-0.1	n/a	n/a	-2.3
			125[5]	ns	-1.4	n/a	n/a	1.7
			200[5]	ns	1.1	n/a	n/a	5.6
Castell et al. (1975), Exp. 2	Canada	$CuSO_4$	125[5]	ns	0.1	n/a	n/a	7.3
			200[5]	ns	-1.9	n/a	n/a	4.8
			125[5]	ns	-1.9	n/a	n/a	-1.3
			200[5]	ns	0.2	n/a	n/a	2.9
Castell et al. (1975), Exp. 3	Canada	$CuSO_4$	125	ns	0.5	1.7	n/a	3.7
			200	ns	0.5	3.3	n/a	3.0
Castell et al. (1975), Exp. 4	Canada	$CuSO_4$	125	ns	1.0	-1.9	n/a	4.1
			200	ns	0.8	-4.6	n/a	12.0
Castell et al. (1975), Exp. 5	Canada	$CuSO_4$	125	ns	0.4	-1.0	n/a	3.4
			200	ns	0.5	-1.9	n/a	2.7
Hansen and Bresson (1975)	Denmark	$CuSO_4$	125	ns	n/a	0.0	n/a	n/a
			200	ns	n/a	2.9	n/a	n/a
Omole et al. (1976)	Nigeria	$CuSO_4$	125	ns	-0.3	2.6	n/a	3.4
			200	ns	0.8	-5.8	n/a	14.5
Barber et al. (1978)	UK	n/a	250	BF	-0.3	-8.1	n/a	n/a
Barber et al. (1981), Exp. 1	UK	$CuSO_4$	250	BF	-0.8	-21.0	n/a	0.6
Barber et al. (1981), Exp. 2	UK	$CuSO_4$	250	ns	0.0	0.0	n/a	n/a
Braude and Hosking (1982)	UK	$CuSO_4$	125	ns	0.4	-3.2	n/a	n/a
			200	ns	0.7	-1.4	n/a	n/a
			200/125	ns	1.1	-2.7	n/a	n/a
			250/125	ns	0.4	-2.7	n/a	n/a
Rowan and Lawrence (1986)	UK	NA	183	ns	-0.4	0.0	n/a	n/a
Astrup and Matre (1987)	Norway	$CuSO_4$	63	ns	1.1	3.1	n/a	n/a
			125	ns	0.7	2.7	n/a	n/a

			250	ns	0.0	-1.0	n/a	n/a
Ward et al. (1991)	USA	$CuSO_4$	250	ns	-0.7	-5.4	1.4	-0.9
Myer et al. (1992)	USA	$CuSO_4$	250	ns	n/a	2.9	n/a	-3.1
Southern et al. (1993)	USA	NA	250	ns	-0.7	n/a	n/a	n/a
Hernández et al. (2009)	Australia	Cu-AA	50[4]	ns	-0.3	-3.4	n/a	n/a
			50[4]	ns	-0.6	-13.6	n/a	n/a
Coble et al. (2014)	USA	$CuSO_4$	50	ns	-0.8	3.1	-0.4	0.0
			125	ns	-0.1	-1.6	0.1	-0.4
		Cu-AA	50	ns	-0.6	3.1	34.7	1.1
Feldpausch et al. (2016)	USA	$CuSO_4$	125[4]	ns	0.2	-0.3	0.4	0.6
			125[4]	ns	-0.1	0.8	0.4	0.9
Coble et al. (2017)	USA	$CuSO_4$/TBCC	75	percentage lean[2], LD[2]	-0.8	-5.8	1.4	2.2
			150		-0.5	-2.6	0.8	2.1
Coble et al. (2018)	USA	TBCC	150	ns	0.2	0.0	0.0	0.6
Coble et al. (2018), Exp. 1	USA	TBCC	150[4]	ns	0.0	-1.8	0.3	-1.1
			150[4]	ns	-0.5	-3.0	1.3	1.2
			150[4]	ns	0.3	1.9	-0.4	2.6
Coble et al. (2018), Exp. 2	USA	TBCC	150[6]	ns	2.2	-6.0	1.3	0.9
			150[6]	ns	-0.2	7.1	-1.2	-1.2
			150[6]	ns	0.9	-6.5	1.3	0.9
			150[6]	ns	-0.4	7.7	-2.7	-2.6
Carpenter et al. (2019)	USA	$CuSO_4$/Cu-AA	70	ns[2]	0.4	0.9	-0.2	0.2
			100		0.4	-0.6	0.1	-0.5
			130		-0.3	-0.3	0.2	0.9
Blavi et al. (2021)	USA	$CuSO_4$	125	ns	0.3	11.5	-1.2	5.5
			250	ns	0.4	-1.8	0.5	3.6
		Cu_2O	125	ns	0.5	1.8	0.1	1.5
			250	ns	0.5	-9.7	1.3	6.6

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]The top two comparisons were the results of the barrows and the bottom two comparisons were the results of the gilts.

[6]The top two comparisons were the results of the feeding Cu in grow-finish phase and the bottom two comparisons were the results of feeding Cu in the finish phase. The basal diet Lys concentrations from the top to bottom comparisons were at 92.5, 100, 92.5, and 100% of the requirement.

6. Zinc (Zn)

There were 13 research articles for Zn with 30 comparisons from 6 countries during the grow-finish or finishing period which met the requirements for inclusion. Of these, 30 comparisons reported growth performance data, and 21 comparisons reported carcass data. The growth-promotive levels of Zn were close to the control Zn levels used in most research (ranged approximately between 50 to 100 mg/kg); therefore, only trials with the total Zn level above or at approximately 100 mg/kg were used in this literature review. The difference in Zn levels between control diets and the growth-promotive Zn diets ranged between 38 to 400 mg/kg. The Zn sources used in the studies were inorganic (ZnO, $ZnSO_4$, Zn-HCl, Zn hydroxy chloride) or organic form (Zinc glycinate, Zn-AA).

6.1. Growth Performance – Zn

Average daily gain significantly increased ($P \leq 0.05$) in 1 comparison (18.7%), tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (1.1%), and significantly decreased ($P \leq 0.05$) in 1 comparison (14.4%) compared to control pigs (Table A.11). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (27 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 12 comparisons (average of 4.0%) and numerically decreased ($P > 0.10$) in 11 comparisons (average of 3.2%) compared to control pigs. Feed efficiency tended to increase ($0.05 < P \leq 0.10$) in 4 comparisons (average of 1.2%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (26 comparisons). Of these, G:F was numerically

increased ($P > 0.10$) in 14 comparisons (average of 4.2%) and numerically decreased ($P > 0.10$) in 11 comparisons (average of 2.6%) compared to control pigs. Overall, the results suggest that Zn had positive but relatively small effects on ADG and G:F. Moreover, there were insufficient data to support whether different types of basal diets and inclusion levels affected the response to Zn for ADG and G:F.

Table A.11. Studies on the effects of Zn on growth performance.

Author	Country	Zn	Basal, mg/kg	Added, mg/kg	Sig.[1]	Difference, %[1]	
						ADG	G:F
Kline et al. (1972)	USA	$ZnSO_4$	100	100[4]	ns	8.1	-5.1
			100	200[4]	ns	-1.8	14.4
			100	100[4]	ns	-8.8	-0.3
			100	200[4]	ns	-9.7	1.3
			100	100[4]	ns	0.0	-3.7
			100	200[4]	ns	5.7	-2.5
Omole et al. (1976)	Nigeria	Zn powder	50	100[4]	ns	11.9	9.0
			50	100[4]	ns	9.7	5.0
Eisemann et al. (1979)	USA	ZnO	100	400	ns	2.7	4.4
Wedekind et al. (1994)	USA	ZnSO4	52	60	ns	-3.4	0.0
Rupić et al. (1997)	Croatia	ZnSO4	37	84	ADG	18.7	3.8
Hernández et al. (2009)	Australia	Zn-AA	70	40[4]	ns	0.2	-1.5
			70	40[4]	ns	1.8	1.5
			70	40[4]	ns	2.7	2.2
			70	40[4]	ns	-3.0	3.7
Paulk et al. (2014)	USA	ZnO	50	75[5]	ns	0.0	-2.9
			50	75[5]	ns	-1.8	-2.1
Feldpausch et al. (2016)	USA	ZnO	110	150[4]	ns	1.0	1.3
			110	150[4]	ns	0.0	-1.3
Holen et al. (2018)	USA	Zn-AA	70	40	ns	2.2	3.7
			70	80	ns	1.1	3.4
		$ZnSO_4$	70	80	ns	2.2	2.5
Cemin et al. (2019)	USA	Zn hydroxychloride/ $ZnSO_4$	113	50	ADG[2,3]	1.1	-0.3
			113	50		0.0	-0.8
Cemin et al. (2019)	USA	Zn hydroxychloride	50	37.5	G:F[2,3]	-2.1	0.5
			50	75		-1.1	1.9
			50	112.5		-1.1	1.4

			50	150		-1.1	0.8
Villagómez-Estrada et al. (2021)	Spain	$ZnSO_4$/Zn-HCl	60	60	ns	-1.4	1.4
Natalello et al. (2022)	Italy	Zn glycinate	22.3	100	ADG	-14.4	-7.6

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]High Zn diet was fed for 72 d in the top comparison and 27 d in the below comparison.

6.2. Carcass Characteristics - Zn

Back-fat significantly increased ($P \leq 0.05$) in 1 comparison (13.1%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (18 comparisons; Table A.12). Of these, BF was numerically increased ($P > 0.10$) in 5 comparisons (average of 1.3%) and numerically decreased ($P > 0.10$) in 11 comparisons (average of 2.9%) compared to control pigs. All the comparisons found no evidence of difference ($P > 0.10$) in ADG (14 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 12 comparisons (average of 1.1%) and numerically decreased ($P > 0.10$) in 1 comparison (0.4%) compared to control pigs. All the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (15 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 11 comparisons (average of 0.9%) and numerically decreased ($P > 0.10$) in 4 comparisons (average of 1.5%) compared to control pigs.

Table A.12. Studies on the effects of Zn on carcass characteristics.

Author	Country	Zn	Basal, mg/kg	Added, mg/kg	Sig.[1]	Difference, %[1]			
						Yield	BF	percentage lean	LMA/LD
Omole et al. (1976)	Nigeria	Zn powder	50	100[4]	ns	-0.5	-5.1	n/a	2.6
			50	100[4]	ns	-0.2	0.9	n/a	-2.9
Hernández et al. (2009)	Australia	Zn-AA	70	40[4]	ns	0.0	3.4	n/a	n/a
			70	40[4]	ns	0.9	-6.0	n/a	n/a
			70	40[4]	ns	-0.3	13.1	n/a	n/a
			70	40[4]	ns	-0.3	-7.6	n/a	n/a
Paulk et al. (2014)	USA	ZnO	50	75[5]	ns	-0.1	-1.7	3.9	0.4
			50	75[5]	ns	1.2	0.8	3.2	-1.8
Feldpausch et al. (2016)	USA	ZnO	110	150[4]	ns	0.1	-1.6	0.1	0.1
			110	150[4]	ns	-0.3	-0.5	0.1	0.4
Holen et al. (2018)	USA	Zn-AA	70	40	ns	-0.4	0.9	0.2	0.8
			70	80	ns	0.3	-3.2	0.3	-0.4
		$ZnSO_4$	70	80	ns	0.5	-2.3	1.3	2.7
Cemin et al. (2019)	USA	Zn hydroxychloride/ $ZnSO_4$	113	50	Yield[2]	1.4	0.0	1.4	0.5
			113	100		1.4	0.0	1.5	0.7
Cemin et al. (2019)	USA	Zn hydroxychloride	50	37.5	ns[2]	-0.3	0.0	0.2	0.6
			50	75		-0.5	-1.7	0.2	-0.9
			50	112.5		-0.1	0.6	0.0	0.7
			50	150		-0.1	-1.7	0.4	0.1
Villagómez-Estrada et al. (2021)	Spain	$ZnSO_4$/Zn-HCl	60	60	ns	0.3	n/a	-0.4	n/a
Natalello et al. (2022)	Italy	Zn glycinate	22.3	100	ns	-0.2	n/a	n/a	n/a

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]High Zn diet was fed for 72 d in the top comparison and 27 d in the below comparison.

Feed Additives – Energy and Lipid Metabolism

This section discusses the feed additives that can potentially improve growth performance and carcass characteristics by affecting the energy and lipid metabolism of grow-finish pigs. The feed additives discussed are betaine, Cr, CLA, and L-carnitine.

1. Betaine

There were 20 research articles for betaine with 37 comparisons from 9 countries during the grow-finish or finishing period with added dietary levels of 0.02 to 1.05 %. Of these, all comparisons reported growth performance data, and 32 comparisons reported carcass data.

1.1. Growth Performance - Betaine

Average daily gain significantly increased ($P \leq 0.05$) in 7 comparisons (average of 10.6%), tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (4.3%), and significantly decreased ($P \leq 0.05$) in 2 comparisons (average of 2.8%) compared to control pigs (Table A.13). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (27 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 10 comparisons (average of 2.4%) and numerically decreased in 15 comparisons (average of 3.3%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 5 comparisons (average of 13.2%) and significantly decreased ($P \leq 0.05$) in 1 comparison (0.4%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (29 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 18

comparisons (average of 2.7%) and numerically decreased in 9 comparisons (average of 2.3%) compared to control pigs. Most comparisons (19 comparisons) had added betaine levels of 0.1 and 0.125%; therefore, the effect of betaine levels is not evaluated. There were insufficient data to support whether different types of basal diets affected the response to betaine for ADG and G:F. However, betaine may have a more beneficial effect on ADG and G:F in limit-fed pigs [176, 177]. In summary, the results suggest that betaine had relatively small positive effects on ADG (1.3% improvement) but may benefit G:F more (2.7% improvement).

Table A.13. Studies on the effects of dietary betaine on growth performance

Authors	Country	Inclusion, %	Sig.[1]	Difference, %[1]	
				ADG	G:F
Smith et al. (1994)	USA	0.100[4]	ADG[3]	5.7	2.4
		0.100[4]	ns	1.1	-1.3
Smith et al. (1994)	USA	0.100	ns	3.3	4.1
Matthews et al. (1998), Exp 1	USA	0.125	ns	-0.5	-3.6
Matthews et al. (1998), Exp 2	USA	0.125	ns	0.0	5.6
Øverland et al. (1999)	Norway	1.050	ns	4.2	2.3
Matthews et al. (2001)	USA	0.250	ns	0.0	0.4
Matthews et al. (2001)	USA	0.125	ns[2]	-3.6	6.7
		0.250		-8.3	3.3
		0.500		-8.3	0.4
Young et al. (2001)	USA	0.140	ns	-1.6	-1.3
Lawrence et al. (2002), Exp 1	USA	0.125[5]	ns	-0.6	2.3
		0.125[5]	ns	3.1	2.7
Lawrence et al. (2002), Exp 2	USA	0.100	ns	0.9	3.8
Siljander-Rasi et al. (2003)	Finland	0.025	ADG[2], GF[2]	-0.5	-0.4
		0.050		6.8	5.6
		0.100		9.7	7.5
Feng et al. (2006)	China	0.125	ns	4.6	1.6
Dunshea et al. (2009)	Australia	0.150	ns	2.1	0.9
Huang et al. (2009)	China	0.125	ADG	5.5	2.6
Nakev et al. (2009)	Bulgaria	0.100[6]	ns	-7.1	n/a
		0.100[6]	ns	-4.5	n/a
Yang et al. (2009)	South Korea	0.200	ADG, G:F	3.3	15.0
		0.400	ADG, G:F	27.5	23.2
		0.600	ADG, G:F	17.6	14.6
Van Heugten (2014), Exp 1	USA	0.200	ns	-2.9	1.2
Van Heugten (2014), Exp 2	USA	0.063	ns[2]	-2.1	-1.3
		0.125		-1.1	-1.6
		0.188		0.8	1.6
Madeira et al. (2015)	USA	0.330	ns	1.1	0.4
Wang et al. (2015)	China	0.100	ns	1.2	0.0
Lothong et al. (2016)	Thailand	0.100	ns	-5.6	-6.3
Mendoza et al. (2017), Exp 1	USA	0.200	ADG	-5.1	-1.1
Mendoza et al. (2017), Exp 2	USA	0.063	ns[2]	-1.2	-1.0
		0.125		-1.8	-3.0
		0.188		-0.1	0.0
Lan and Kim (2018)	South Korea	0.100	ADG	3.7	2.9

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]The top comparison used a solid form of betaine and the bottom comparison used a liquid form betaine.

[5]Treament diets were fed from 82 to 106 kg in the top comparison and fed from 104 to 116 kg in the bottom comparison.

[6]The top comparison represented male pigs and the bottom comparison represented female pigs.

1.2. Carcass Characteristics - Betaine

Back-fat significantly decreased ($P \leq 0.05$) in 3 comparisons (average of 10.7%) compared to control pigs (Table A.14). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (29 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 13 comparisons (average of 2.0%) and numerically decreased in 16 comparisons (average of 2.9%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in 1 comparison (5.2%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (24 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 15 comparisons (average of 3.6%) and numerically decreased in 8 comparisons (average of 1.2%) compared to control pigs. Loin muscle area/depth tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (6.3%) and significantly decreased ($P \leq 0.05$) in 3 comparisons (average of 2.3%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (20 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 10 comparisons (average of 1.9%) and numerically decreased in 10 comparisons (average of 2.2%) compared to control pigs

Table A.14. Studies on the effects of dietary betaine on carcass characteristics.

Authors	Country	Inclusion, %	Sig.[1]	Difference, %[1]			
				Yield	BF	percentage lean	LMA/LD
Smith et al. (1994)	USA	0.100[4]	LMA[3]	n/a	-3.2	1.6	6.3
		0.100[4]	ns	n/a	0.8	2.6	8.9
Smith et al. (1994)	USA	0.100	ns	n/a	-3.2	0.5	-1.6
Matthews et al. (1998), Exp 1	USA	0.125	Yield	0.9	1.4	-0.2	0.5
Matthews et al. (1998), Exp 2	USA	0.125	ns	0.0	2.3	-0.6	2.1
Øverland et al. (1999)	Norway	1.050	ns	1.2	0.7	0.8	n/a
Matthews et al. (2001)	USA	0.250	ns	-0.4	4.8	-1.1	-0.4
Matthews et al. (2001)	USA	0.125	BF[2]	-1.5	-4.3	1.2	-3.0
		0.250		1.1	-18.2	5.2	0.7
		0.500		0.1	-12.6	-0.8	-5.6
Lawrence et al. (2002), Exp 1	USA	0.125[5]	ns	0.3	-0.4	0.6	1.5
		0.125[5]	ns	0.0	-0.4	-1.6	-0.4
Lawrence et al. (2002), Exp 2	USA	0.100	BF	n/a	-3.2	n/a	-0.4
Siljander-Rasi et al. (2003)	Finland	0.025	ns[2]	n/a	-3.0	n/a	n/a
		0.050		n/a	1.0	n/a	n/a
		0.100		n/a	-3.0	n/a	n/a
Feng et al. (2006)	China	0.125	ns	0.6	-7.0	2.1	2.2
Dunshea et al. (2009)	Australia	0.150	ns	n/a	4.5	0.9	n/a
Huang et al. (2009)	China	0.125	BF, percentage lean	0.6	-10.3	5.2	n/a
Nakev et al. (2009)	Bulgaria	0.100[6]	ns	ns	0.2	-6.3	2.4
		0.100[6]	ns	ns	5.4	7.4	-4.8
Van Heugten (2014), Exp 1	USA	0.200	ns	-0.4	1.8	-0.2	0.7
Van Heugten (2014), Exp 2	USA	0.063	LD[2]	-0.5	-3.4	0.2	-1.5
		0.125		-0.3	-1.5	0.0	-1.5
		0.188		-0.1	-3.9	0.2	-3.9
Madeira et al. (2015)	USA	0.330	ns	0.2	-1.5	n/a	n/a
Wang et al. (2015)	China	0.100	ns	3.4	0.8	n/a	n/a

Lothong et al. (2016)	Thailand	0.125	BF	n/a	-18.6	n/a	n/a
Mendoza et al. (2017), Exp 1	USA	0.200	ns	0.1	0.9	-0.1	0.2
Mendoza et al. (2017), Exp 2	USA	0.063	ns[2]	-0.7	0.2	11.4	-2.1
		0.125		-0.4	0.2	11.6	-1.3
		0.188		-0.3	1.3	12.4	-0.6

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.
[2]Polynomial contrasts were used for statistical analysis.
[3]Significant level at $0.05 < P \leq 0.10$.
[5]The top comparison used a solid form of betaine and the bottom comparison used a liquid form betaine.
[4]Treament diets were fed from 82 to 106 kg in the top comparison and fed from 104 to 116 kg in the bottom comparison.
[6]The top comparison represented male pigs and the bottom comparison represented female pigs.

2. Chromium (Cr)

There were 50 research articles for Cr with 139 comparisons from 9 countries during the grow-finish or finishing period with added dietary levels of 25 to 1,000 µg/kg (1 experiment used 5,000 µg/kg Cr as an overdose trial). Of these, 139 comparisons reported growth performance data, and 133 comparisons reported carcass data. The sources of Cr were Cr picolinate, Cr propionate, Cr nicotinate, Cr methionine, Cr yeast, $CrCl_3$, Cr nanocomposites, Cr sulfate, and Cr bis-glycinate-nicotinamide chelate.

2.1. Growth Performance - Cr

Average daily gain significantly increased ($P \leq 0.05$) in 14 comparisons (average of 8.9%), tended to increase ($0.05 < P \leq 0.10$) in 4 comparisons (average of 4.6%), significantly decreased ($P \leq 0.05$) in 7 comparisons (average of 7.2%), and tended to decrease ($0.05 < P \leq 0.10$) in 5 comparisons (average of 4.1%) compared to control pigs (Table A.15). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (109 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 51 comparisons (average of 3.6%) and numerically decreased ($P > 0.10$) in 48 comparisons (average of 2.2%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 14 comparisons (average of 5.2%) and significantly decreased ($P \leq 0.05$) in 7 comparisons (average of 4.3%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (117 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in

60 comparisons (average of 3.1%) and numerically decreased ($P > 0.10$) in 41 comparisons (average of 2.1%) compared to control pigs. These studies found no evidence of difference because Cr's effects were not large enough and variation in performance was too great. Also, the basal diets might have provided enough Cr to meet the requirement; therefore, increasing the level of Cr did not have a significant effect on ADG and G:F [195-200]. Overall, the data suggest that Cr positively affected ADG and G:F, but the effects were small and inconsistent. The addition of 50 to 400 μg/kg Cr in diets was most common and had better improvement on ADG and GF compared to the higher levels. However, there were not enough comparisons at greater Cr levels to fully determine the effect of high Cr levels. Moreover, toxicity of Cr at a high inclusion level (5,000 μg/kg) was not observed [201]. Chromium chelated with methionine or in nanoparticle form may provide a more consistently positive effect on ADG; however, Cr form did not seem to affect the consistency of the G:F response. According to our database, Cr minorly improved ADG and G:F of pigs (approximately 1% improvement). This is in agreement with a meta-analysis that analyzed data from 31 studies and found that grow-finish pigs fed 200 to 500 μg/kg Cr had improved ($P \leq 0.05$) ADG and G:F compared to the control pigs [202].

Table A.15. Studies on the effects of dietary chromium on growth performance.

Authors	Country	Source	Inclusion, µg/kg	Sig.[1]	Difference, %	
					ADG	G:F
Page et al. (1993), Exp. 1	USA	Picolinate	25	ADG[2]	0.0	6.9
			50		4.1	4.5
			100		-5.9	-0.3
			200		7.8	5.5
Page et al. (1993), Exp. 2	USA	Picolinate	100	ADG[2]	-1.2	2.1
			200		-0.7	-0.3
			400		-6.2	5.4
			800		-9.1	-0.9
Page et al. (1993), Exp. 3	USA	$CrCl_3$	200[4]	ns	6.0	6.4
			200[4]	ns	4.2	1.2
	USA	Picolinate	100 and 200	ns	5.9	-2.7
Smith et al. (1994)	USA	Nicotinate	200	ns	2.0	1.7
Boleman et al. (1995)	USA	Picolinate	200[5]	ADG	-6.4	0.0
			200[5]	ns	-5.8	3.2
Lindemann et al. (1995), Exp. 1	USA	Picolinate	250	ns[2]	1.0	8.1
			500		-3.1	6.4
Lindemann et al. (1995), Exp. 2	USA	Picolinate	200[4]	ns	-2.4	6.8
			200[4]	ns	-1.2	-2.3
Lindemann et al. (1995), Exp. 3	USA	Picolinate	100	ns[2]	1.2	-0.3
			500		1.2	-2.9
			1000		-2.4	-1.1
Mooney and Cromwell (1995)	USA	Picolinate	200	ADG[3]	5.4	1.9
Smith et al. (1996)	USA	Nicotinate	200	ns	-1.7	-0.2
Kornegay et al. (1997)	USA	Picolinate	200	ns	2.5	n/a
Min et al. (1997)	South Korea	Picolinate	100	ns	-0.7	0.3
			200	ns	-3.3	0.3
			400	ns	-0.5	2.5
Mooney and Cromwell (1997)	USA	Picolinate	200	ns	2.3	1.4
		$CrCl_3$	5,000	ns	-1.1	-1.4
Ward et al. (1997)	USA	Picolinate	400[4]	ns	1.9	5.7
			400[4]	ns	-2.1	-5.4
			400[4]	ns	4.0	3.9
			400[4]	ns	-1.7	-2.7
Lien et al. (1998)	Taiwan	Picolinate	200	ns	-1.9	10.3
O'Quinn et al. (1998)	USA	Nicotinate	50	ADG[2,3]	4.6	1.1
			100		-2.1	-0.9
			200		-3.6	-1.7
			400		-3.2	0.2
		Picolinate	200	ns	-0.8	-1.6
Lemme et al. (1999)	USA	Yeast	200	ADG[3], G:F	5.9	6.5
			400	ns	0.1	1.8

			800	ns	-0.7	1.1
Mooney and Cromwell (1999), Exp.1	USA	Picolinate	200	ns	-0.6	-2.6
Mooney and Cromwell (1999), Exp.2	USA	Picolinate	200	ns	-1.2	1.1
O'Quinn et al. (1999)	USA	Nicotinate	50[4]	G:F	0.7	4.4
			50[4]	G:F	4.7	6.8
Hanczakowska et al. (1999)	Poland	Yeast	(0.03%)	G:F	2.2	-4.7
		Picolinate	200[4]	ns	-0.5	-0.3
			200[4]	ns	0.0	0.0
Matthews et al. (2001)	USA	Picolinate	200	ns	0.0	-1.4
		Propionate	200	ns	-1.1	2.4
Xi et al. (2001)	USA	Picolinate	200	ns	3.6	3.1
Matthews et al. (2003)	USA	Propionate	200	ns	-0.5	1.4
Shelton et al. (2003), Exp. 1	USA	Propionate	50	ns[2]	-2.5	3.3
			100		0.0	3.3
			200		-2.5	3.3
			200[4]	ns	-2.5	3.3
			200[4]	ns	-2.6	3.6
Shelton et al. (2003), Exp. 2	USA	Propionate	100	ns[2]	1.0	-5.6
			200		-1.0	-2.8
			300		-1.0	-2.8
Waylan et al. (2003)	USA	Nicotinate	50	G:F	2.9	5.4
Groesbeck et al. (2004)	USA	Picolinate	100	ns[2]	-2.6	1.8
			200		-3.7	-1.5
		Propionate	100	ns[2]	0.0	0.3
			200		-1.6	-0.9
Wang and Xu (2004)	China	Nano Cr	200	G:F	5.6	3.7
Matthews et al. (2005)	USA	Propionate	200	ns	0.0	2.6
Amoikon et al. (2006)	USA	Picolinate	200[4]	ns	2.5	-3.4
			200[4]	ns	-5.6	0.0
			200[4]	ns	-2.3	0.0
Khajarern et al. (2006)	Thailand	Bisglycinate-nicotinamide chelate	200	ns	-0.1	0.3
			400	ns	1.1	1.4
Bergstrom et al. (2008)	USA	Propionate	200	ns	1.0	1.2
Lindemann et al. (2008)	USA	Picolinate	5,000	ns	6.0	0.6
		Propionate	5,000	ns	5.8	2.3
		Methionine	5,000	ns	0.3	-2.9
		Yeast	5,000	ADG	8.6	0.6
Wang et al. (2008)	China	Picolinate	200	ADG	9.8	4.8
Jackson et al. (2009)	USA	Propionate	200[4]	ns	-0.8	1.5
			200[4]	ns	-2.8	-5.1
			200[4]	ns	6.2	1.4
Park et al. (2009)	South Korea	$CrCl_3$	200	ns	3.1	2.0
		Picolinate	200	ADG, G:F	7.8	6.2

		Methionine	100	ADG, G:F	4.7	3.2
			200	ADG, G:F	6.3	6.2
Wang et al. (2009)	China	$CrCl_3$	200	ns	-0.3	-2.5
		Picolinate	200	ns	2.3	-2.0
		Nano $CrCl_3$	200	ns	6.4	4.8
Wang et al. (2009)	China	$CrCl_3$	200	ns	-0.3	0.9
		Nano Cr	200	ADG, G:F	6.3	9.5
Li et al. (2013)	China	Methionine	300	ADG[2], G:F[2]	4.1	-1.7
			600		16.0	-3.6
			900		20.5	-4.6
Panaite et al. (2013)	Romania	Picolinate	200	ns	-9.0	-3.3
			400	ADG, G:F	-21.1	-10.3
Hung et al. (2014)	Australia	Nano Picolinate	400	ADG[3]	5.3	-0.4
Peres et al. (2014)	Brazil	Sulfate	200	ns	-0.9	0.4
		Methionine	200	ADG, G:F	5.3	7.3
Wang et al. (2014)	China	Cr chitosan nanoparticles	100	G:F[2]	1.3	3.4
			200		-0.1	4.1
			400		-0.5	3.4
Tian et al. (2015)	China	Methionine	100	ns[2]	2.9	-1.2
			200		4.3	0.3
			400		1.4	-1.5
			800		1.4	0.0
Li et al. (2017)	Taiwan	$CrCl_3$	200	ns	13.6	0.0
		Picolinate	200	ns	13.6	3.6
		Nano $CrCl_3$	200	ns	10.6	0.0
		Nano picolinate	200	ADG	21.2	3.6
Marcolla et al. (2017)	Brazil	Yeast	400[4]	ns	-4.0	-3.9
			400[4]	ns	-4.0	0.0
Xu et al. (2017)	China	Methionine	200	ns	1.4	4.4
Jin et al. (2018)	China	Methionine	200[4]	ns	-3.7	-1.0
			200[4]	ns	-0.9	5.1
Gebhardt et al. (2019), Exp. 1	USA	Propionate	200	ns	0.6	-1.3
Gebhardt et al. (2019), Exp. 2	USA	Propionate	200[4]	ns	0.0	2.8
			200[4]	ns	0.0	0.0
			200[4]	ns	2.3	0.0
Gebhardt et al. (2019), Exp. 1	USA	Propionate	100	G:F[2]	1.1	2.5
			200		0.0	0.0
			100/200	ns	1.1	0.0
			200/100	ns	0.0	0.0
Gebhardt et al. (2019), Exp. 2	USA	Propionate	200/100	ns	1.1	0.0
			200	ADG	2.2	0.0
Lien and Lan (2019)	Taiwan	Picolinate	200	ns	11.3	1.1
		Nano picolinate	200	ns	7.6	-3.7
Mayorga et al. (2019)	USA	Propionate	200	ns	3.4	4.0
da Silva et al. (2021)	Brazil	Yeast	800	ns	2.0	7.1

		Picolinate	480	ns	-4.9	7.5
Santos et al. (2021)	USA	Propionate	200[4]	ADG[3], G:F	-1.0	-2.3
			200[4]	ADG[3], G:F	-3.2	-2.9
Alencar et al. (2022)	Brazil	Yeast	800[4]	ns	-3.9	-1.9
			800[4]	ns	2.0	-1.5

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]The comparison was the result of Cr fed in grow-finish phase and bottom comparison was the result of Cr fed in finish phase.

2.2. Carcass Characteristics - Cr

Back-fat significantly increased ($P \leq 0.05$) in 2 comparisons (average of 8.0%), tended to increase ($0.05 < P \leq 0.10$) in 5 comparisons (average of 6.3%), significantly decreased ($P \leq 0.05$) in 22 comparisons (average of 14.4%), and tended to decrease ($0.05 < P \leq 0.10$) in 7 comparisons (average of 12.4%) compared to control pigs (Table A.16). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (97 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 42 comparisons (average of 4.2%) and numerically decreased ($P > 0.10$) in 53 comparisons (average of 6.4%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in 20 comparisons (average of 6.6%), tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (5.0%), and significantly decreased ($P \leq 0.05$) in 2 comparisons (average of 4.1%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (82 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 43 comparisons (average of 1.9%) and numerically decreased ($P > 0.10$) in 36 comparisons (average of 1.2%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 23 comparisons (average of 13.9%) and significantly decreased ($P \leq 0.05$) in 1 comparison (11.6%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (101 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 61 comparisons (average of 3.2%) and numerically decreased ($P > 0.10$) in 38 comparisons (average of 3.0%) compared to control

pigs. According to the database, Cr decreased BF, and increased percentage lean, and LMA/LD of grow-finish pigs in more than 60% of the comparisons, and the effects were observed across all inclusion levels (25 to 5,000 µg/kg). Additionally, increasing the Cr level improved the carcass characteristics linearly within the 50 to 400 µg/kg inclusion (approximately 80% of all comparisons). Different Cr sources may not have the same effect on carcass characteristics. Contrary to the overall effects, Cr nicotinate increased BF by 2.2% (13 comparisons), and $CrCl_3$ decreased LMA/LD by 2.2% (6 comparisons). The meta-analysis conducted by Sales and Jančík [202] also found Cr reduced ($P < 0.001$) 10th rib BF and increased ($P < 0.001$) percentage lean and LMA.

Table A.16. Studies on the effects of dietary chromium on carcass characteristics.

Author	Country	Source	Inclusion, µg/kg	Sig.[1]	Difference, %[1]			
					Yield	BF	percentage lean	LMA/LD
Page et al. (1993), Exp. 1	USA	Picolinate	25	ns[2]	n/a	-14.5	3.4	2.9
			50		n/a	-17.7	3.0	1.1
			100		n/a	-6.0	1.9	-2.0
			200		n/a	-13.8	2.6	6.6
Page et al. (1993), Exp. 2	USA	Picolinate	100	Yield[2,3], BF[2], percentage lean[2], LMA[2]	0.8	-25.7	8.5	18.8
			200		2.3	-16.5	5.8	17.4
			400		3.3	-30.2	11.0	22.6
			800		3.2	-21.9	8.7	18.5
Page et al. (1993), Exp. 3	USA	$CrCl_3$	200[4]	ns	0.0	-5.5	0.0	-1.0
			200[4]	ns	-1.1	5.4	-1.9	-3.5
		Picolinate	100 and 200	BF, percentage lean, LMA	0.1	-19.7	5.6	21.4
Smith et al. (1994)	USA	Nicotinate	200	BF	n/a	-8.8	4.1	3.3
Lindemann et al. (1995)	USA	Picolinate	250	ns[2]	n/a	2.4	n/a	3.3
			500		n/a	9.0	n/a	3.8
Lindemann et al. (1995)	USA	Picolinate	200[4]	BF, percentage lean, LMA	n/a	-17.3	8.9	15.9
			200[4]	BF, percentage lean, LMA	n/a	-10.3	4.7	6.6
Lindemann et al. (1995)	USA	Picolinate	100	BF[2], percentage lean[2], LMA[2]	n/a	-5.5	1.8	3.3
			500		n/a	12.7	-7.4	-11.6
			1,000		n/a	-13.9	5.8	5.3
Mooney and Cromwell (1995)	USA	Picolinate	200	ns	n/a	-0.5	n/a	-2.3
Boleman et al. (1995)	USA	Picolinate	200[5]	ns	0.1	7.6	-0.5	1.7
			200[5]	percentage lean[3]	0.1	-8.9	5.0	7.3
Smith et al. (1996)	USA	Nicotinate	200	ns	0.0	2.1	0.5	-1.1
Kornegay et al. (1997)	USA	Picolinate	200	ns	-0.4	3.9	0.0	6.8

Mooney and Cromwell (1997)	USA	Picolinate	200	LMA[3]	-0.5	0.3	2.1	6.3
		$CrCl_3$	5000	LMA[3]	-0.4	-3.0	1.9	6.2
Ward et al. (1997)	USA	Picolinate	400[4]	ns	0.5	-6.5	-0.2	-1.3
			400[4]	ns	-0.4	0.0	-0.2	-4.3
			400[4]	ns	-0.4	3.8	0.0	2.2
			400[4]	ns	0.1	15.0	-1.4	0.0
Min et al. (1997)	South Korea	Picolinate	100	ns	0.3	-4.9	n/a	1.8
			200	ns	0.4	-15.9	n/a	6.6
			400	ns	-0.3	-11.4	n/a	3.1
Lien et al. (1998)	Taiwan	Picolinate	200	BF, LMA	n/a	-9.4	n/a	12.1
O'Quinn et al. (1998), Exp.1 (barrow)	USA	Nicotinate	50	ns[2]	0.2	2.0	-1.3	-1.3
			100		-1.2	8.1	-2.3	-5.7
			200		0.0	2.0	-0.4	-4.9
			400		0.9	-1.0	0.2	0.6
O'Quinn et al. (1998), Exp. 1 (gilt)	USA	Nicotinate	50	Yield[2]	0.0	5.5	-2.0	-3.9
			100		0.9	6.6	-1.2	1.9
			200		1.5	6.6	-1.6	-2.5
			400		0.3	4.4	1.1	2.7
O'Quinn et al. (1998), Exp. 2[12]	USA	Picolinate	200	ns	0.0	3.8	-1.1	-1.9
Hanczakowska et al. (1999)	Poland	Yeast	(0.03%)	ns	n/a	1.4	-0.3	2.0
		Picolinate	200[4]	ns	n/a	-1.8	1.9	4.9
			200[4]	ns	n/a	4.7	-2.5	-5.1
Mooney and Cromwell (1999), Exp. 1	USA	Picolinate	200	ns	0.2	-0.3	0.9	5.4
Mooney and Cromwell (1999), Exp. 2	USA	Picolinate	200	ns	-0.2	3.8	-1.6	-1.8
O'Quinn et al. (1999)	USA	Nicotinate	50[4]	ns	0.7	-0.5	0.1	2.3
			50[4]	ns	-0.7	1.0	0.5	2.6
Lemme et al. (1999)	USA	Yeast	200	Yield[3]	-1.6	5.0	n/a	n/a
			400	ns	0.2	-1.1	n/a	n/a
			800	ns	0.6	3.9	n/a	n/a
	USA	Picolinate	200	ns	0.4	-7.7	-2.8	0.7

Matthews et al. (2001), Exp. 1		Propionate	200	ns	-0.3	-7.7	-0.6	6.1
Xi et al. (2001)	USA	Picolinate	200	BF, percentage lean, LMA	1.2	-10.9	7.6	15.6
Matthews et al. (2003)	USA	Propionate	200	ns	-0.2	0.6	-1.8	-1.0
Shelton et al. (2003), Exp. 1	USA	Propionate	50	ns[2]	0.3	-3.5	2.4	3.8
			100		0.1	2.0	-1.4	0.7
			200		0.1	-2.3	3.0	9.9
			200[4]	ns	0.1	-2.3	3.0	9.9
			200[4]	ns	-1.5	-4.9	0.7	-6.1
Shelton et al. (2003), Exp. 2	USA	Propionate	100	ns[2]	-0.1	7.8	-2.4	-2.6
			200		-0.2	3.7	0.1	2.3
			300		0.2	1.8	0.1	1.7
Waylan et al. (2003)	USA	Nicotinate	50	ns	0.0	0.2	0.3	2.5
Wang and Xu (2004)	China	Nano Cr	200	BF, percentage lean, LMA	1.2	-18.2	14.1	20.0
Matthews et al. (2005)	USA	Propionate	200	ns	-0.4	10.2	-0.6	-4.3
Amoikon et al. (2006)	USA	Picolinate	200[4]	ns	-1.9	-2.3	-0.5	-0.9
			200[4]	ns	-0.8	7.2	-3.5	-7.0
			200[4]	ns	1.9	-0.3	0.5	-1.1
Khajarern et al. (2006)	Thailand	Bisglycinate-nicotinamide chelate	200	Yield[2], BF[2], LMA[2]	0.0	-4.5	2.2	5.9
			400		0.9	-7.3	3.1	7.3
Bergstrom et al. (2008)	USA	Propionate	200	ns	0.7	1.4	-0.7	-3.3
Wang et al. (2008)	China	Picolinate	200	LMA	2.7	-10.3	n/a	17.3
Lindemann et al. (2008)	USA	Tripicolinate	5,000	ns	0.6	-7.3	n/a	2.0
		Propionate	5,000	ns	1.1	-16.0	n/a	0.2
		Methionine	5,000	ns	0.9	-3.8	n/a	-2.6
		Yeast	5,000	ns	0.3	-10.3	n/a	1.3
Jackson et al. (2009)	USA	Propionate	200[4]	BF[3]	0.5	-6.3	2.6	6.1
			200[4]	BF[3]	0.2	-9.1	-2.4	3.1
			200[4]	BF[3]	1.1	1.6	-1.5	3.2
Park et al. (2009)	South Korea	$CrCl_3$	200	ns	-1.4	-12.6	1.6	-5.6

		Picolinate	200	ns	0.9	-13.7	3.2	1.6
		Methionine	100	ns	1.2	-15.5	3.1	2.1
			200	BF, percentage lean	0.7	-31.4	8.8	2.5
Wang et al. (2009)	China	$CrCl_3$	200	ns	1.3	-2.7	3.5	-5.4
		Picolinate	200	LMA	3.1	-10.3	1.7	17.3
		Nano $CrCl_3$	200	BF, percentage lean, LMA	1.5	-24.3	10.6	20.2
Panaite et al. (2013)	Romania	Picolinate	200	ns	n/a	-3.9	0.9	n/a
			400	ns	n/a	-16.5	2.9	n/a
Li et al. (2013)	China	Methionine	300	$BF^{2,3}$, LMA^2	-1.0	-15.4	3.4	7.2
			600		0.3	-19.1	7.2	13.2
			900		-0.1	-22.8	7.3	13.1
Hung et al. (2014)	Australia	Nano Tripicolinate	400	ns	0.0	0.0	n/a	n/a
Peres et al. (2014)	Brazil	Cr sulfate	200	ns	-0.4	-0.6	n/a	-0.4
		Methionine	200	ns	-0.4	-3.8	n/a	0.1
Wang et al. (2014)	China	Chitosan nanoparticles	100	BF^2, percentage $lean^2$, LMA^2	1.1	-5.2	3.2	13.5
			200		1.1	-8.1	3.7	15.8
			400		1.0	-7.6	3.2	11.5
Tian et al. (2015)	China	Methionine	100	$BF^{2,3}$	-1.5	7.4	-0.8	-1.4
			200		-1.2	14.5	1.9	16.3
			400		-0.8	-10.9	3.8	6.1
			800		-0.5	-3.3	2.1	6.8
Li et al. (2017)	Taiwan	$CrCl_3$	200	ns	1.2	-0.4	n/a	-3.7
		Picolinate	200	BF	1.2	-9.6	n/a	-3.7
		Nano $CrCl_3$	200	ns	0.9	-0.9	n/a	-3.3
		Nano Picolinate	200	BF	0.9	-9.6	n/a	0.2
Marcolla et al. (2017)	Brazil	Yeast	400^4	ns	-0.1	-24.5	n/a	-0.3
			400^4	ns	-0.3	10.2	n/a	-6.4
Xu et al. (2017)	China	Methionine	200	ns	1.1	-5.2	n/a	2.1
Jin et al. (2018)	China	Methionine	200^4	Yield	3.2	11.9	n/a	n/a
			200^4	ns	0.9	-8.2	n/a	n/a
Mayorga et al. (2019)	USA	Propionate	200	ns	n/a	-0.8	n/a	0.4

Gebhardt et al. (2019), Exp. 1	USA	Propionate	200	BF, percentage lean	0.6	3.3	-0.8	-1.0
Gebhardt et al. (2019), Exp. 2	USA	Propionate	200[4]	ns	-0.3	0.8	-0.1	0.0
			200[4]	ns	0.3	0.7	-0.1	0.1
			200[4]	ns	-0.5	1.5	-0.5	-1.9
Gebhardt et al. (2019), Exp. 1	USA	Propionate	100	ns[2]	0.1	0.3	0.1	1.3
			200		-0.5	-0.4	0.2	0.8
			100/200	ns	-0.1	0.6	0.1	1.2
			200/100	ns	-0.3	-0.2	0.2	1.3
Gebhardt et al. (2019), Exp. 2	USA	Propionate	200/100	ns	0.0	-2.2	0.6	1.2
			200/200	Yield	-0.4	1.1	-0.2	0.5
Lien and Lan (2019)	Taiwan	Picolinate	200	ns	-1.5	-9.7	-0.7	0.0
		Nano Picolinate	200	ns	-0.6	-11.1	-1.4	4.5
da Silva et al. (2021)	Brazil	Yeast	800	percentage lean	n/a	0.7	5.9	3.2
		Picolinate	480	percentage lean	n/a	-12.8	7.9	1.7
Santos et al. (2021)	USA	Propionate	200[4]	BF[3]	0.4	6.1	-0.7	1.5
			200[4]	BF[3]	-0.3	1.9	-0.6	-1.4
Alencar et al. (2022)	Brazil	Yeast	800[4]	ns	1.2	-1.4	-0.4	-2.5
			800[4]	ns	-1.0	-1.5	0.2	-1.9

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]The 2 experimental diets with Cr were fed in grow-finish and finish phase respectively.

3. Conjugated Linoleic Acid (CLA)

There were 46 research articles for CLA with 73 comparisons from 15 countries during the grow-finish or finishing period with added dietary levels of 0.07 to 2.72%. Of these, 55 comparisons reported growth performance data, and 65 comparisons reported carcass data.

3.1. Growth Performance - CLA

Average daily gain significantly increased ($P \leq 0.05$) in 5 comparisons (average of 7.2%), tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (3.6%), and significantly decreased ($P \leq 0.05$) in 3 comparisons (average of 7.8%) compared to control pigs (Table A.17). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (53 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 34 comparisons (average of 3.7%) and numerically decreased ($P > 0.10$) in 17 comparisons (average of 4.1%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 13 comparisons (average of 4.5%), tended to increase ($0.05 < P \leq 0.10$) in 6 comparisons (average of 8.8%), and significantly decreased ($P \leq 0.05$) in 1 comparison (2.8%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (37 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 24 comparisons (average of 4.6%) and numerically decreased ($P > 0.10$) in 9 comparisons (average of 2.3%) compared to control pigs. Overall, the results suggest that CLA had positive effects on ADG and G:F (65 and 75% of all the comparisons); however, the effects of CLA were often not significant enough to statistically

improve ($P < 0.10$) ADG (10% of all the comparisons). On the other hand, CLA improved ($P < 0.10$) G:F in 33% of all the comparisons. Increasing CLA concentrations did not increasingly improve the ADG and G:F response. Contrary to what is concluded herein, in a meta-analysis by Wang et al. [245] found no evidence of difference ($P > 0.05$) in ADG, ADFI, and G:F when pigs were fed CLA or linseed supplementation; however, only seven research articles were included in their meta-analysis. Different basal diets may affect the response to CLA on ADG and G:F. Diets with wheat as the main ingredient (18 comparisons) had a greater percentage of improvement in ADG (3.7%) and G:F (5.4%) compared to diets with corn as the main ingredient [ADG decreased 0.1% (32 comparisons) and G:F increased 2.8% (28 comparisons)].

Table A.17. Studies on the effects of dietary CLA on growth performance.

Author	Country	Inclusion, %	Sig.[1]	Difference, %[1]	
				ADG	G:F
Dugan et al. (1997)	Canada	1.00	G:F[3]	0.0	6.2
Ostrowska et al. (1999)	Australia	0.07	ns[2]	10.2	5.8
		0.14		6.3	6.7
		0.28		8.4	8.8
		0.41		1.4	3.0
		0.55		2.8	6.7
O'Quinn et al. (2000)	USA	0.30	ns	-5.8	0.0
Bee (2001)	Switzerland	1.20	ns	7.5	6.8
Eggert et al. (2001)	USA	0.60	ADG	-10.2	-7.4
Dugan et al. (2001)	Canada	0.16[4]	ns	1.5	4.0
		0.33[4]	ns	4.0	2.1
		0.16[4]	ns	5.0	0.3
		0.33[4]	ns	0.7	2.0
Thiel-Cooper et al. (2001)	USA	0.07	ns	-1.3	4.3
		0.15	ns	1.2	6.0
		0.30	ns	3.4	5.1
		0.60	ADG, G:F	8.2	9.1
Wiegand et al. (2001)	USA	0.75	G:F	1.9	6.1
Barowicz et al. (2002)	Poland	1.20	ns	4.3	10.5
		1.20	ns	1.2	0.8
Dunshea et al. (2002), Exp. 1	Australia	0.22	ns	1.4	4.1
Dunshea et al. (2002), Exp. 2	Australia	0.22	ns	-1.4	-0.7
Tischendorf et al. (2002)	Germany	1.08	ns	2.0	0.3
Wiegand et al. (2002)	USA	0.75[5]	G:F[2]	0.5	2.7
		0.75[5]		1.9	3.3
		0.75[5]		-1.3	1.2
Ostrowska et al. (2003)	Australia	0.07	G:F[2,3]	6.1	6.7
		0.14		5.8	10.0
		0.28		6.8	16.7
		0.41		-0.1	3.3
		0.55		-2.0	10.0
Sun et al. (2004)	China	1.36	ADG[2], G:F[2]	7.7	3.9
		2.72		14.1	5.2
Barowicz et al. (2005)	Poland	1.20	ns	1.2	n/a
Lauridsen et al. (2005)	Denmark	0.30	ADG[3], G:F	3.6	4.8
Weber et al. (2006)	USA	0.60	G:F	3.4	4.0
Bee et al. (2008)	Switzerland	0.60	ns	2.5	0.0
Corino et al. (2008)	Italy	0.38	ns	2.2	n/a
Martin et al. (2008)	Spain	0.56	ns	5.1	5.9
		1.12	ns	5.7	5.9

White et al. (2009)	USA	0.60	ns	5.4	-1.4
Jiang et al. (2010)	China	1.00	ADG[2]	-7.9	0.0
		2.00		-5.3	-1.6
Han et al. (2011)	China	0.36	ns[2]	-6.6	n/a
		0.71		-14.5	n/a
		1.09		-9.2	n/a
Lee et al. (2011)	South Korea	0.59	ns	3.7	12.5
Barnes et al. (2012)	USA	0.60	G:F	-3.2	-2.8
Go et al. (2012)	USA	0.80	ns	-3.2	-2.7
Martinez-Aispuro et al. (2012)	Mexico	1.2/0.5/0.2	ns	-9.4	-2.0
Rickard et al. (2012)	USA	0.36	G:F	1.6	5.8
Pompeu et al. (2013)	USA	0.60[4]	ADG, G:F	1.6	2.2
		0.60[4]	ADG, G:F	4.4	2.3
Tous et al. (2013)	Spain	2.51	ns	0.0	-2.5
Martínez-Aispuro et al. (2014)	Mexico	0.60	ns	-1.9	-2.2
Wang et al. (2015)	China	0.60	ns	1.2	0.0
Marcolla et al. (2017)	Brazil	0.28[4]	ns	5.0	3.9
		0.28[4]	G:F	4.9	8.1
Upadhaya et al. (2017)	South Korea	0.28	ns	-0.5	1.2
		0.56	ns	-0.8	-0.3
Panisson et al. (2020)	Brazil	0.18	ns	-3.4	2.0
		0.36	ns	-5.5	2.0

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]CLA was fed in the 3 treatment diets during the last 29, 56, or 87 kg of BW gain before slaughter respectively.

3.2. Carcass Characteristics - CLA

Back-fat significantly decreased ($P \leq 0.05$) in 22 comparisons (average of 15.4%) and tended to decrease ($0.05 < P \leq 0.10$) in 5 comparisons (average of 6.5%) compared to control pigs (Table A.18). Approximately half of the studies found no evidence of difference ($P > 0.10$) in BF (32 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 14 comparisons (average of 4.0%) and numerically decreased ($P > 0.10$) in 16 comparisons (average of 6.1%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in 14 comparisons (average of 4.9%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (23 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 16 comparisons (average of 1.9%) and numerically decreased ($P > 0.10$) in 7 comparisons (average of 0.6%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 6 comparisons (average of 7.6%), tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (3.7%), significantly decreased ($P \leq 0.05$) in 1 comparison (5.9%), and tended to decrease ($0.05 < P \leq 0.10$) in 1 comparison (4.8%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (29 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 14 comparisons (average of 3.0%) and numerically decreased ($P > 0.10$) in 15 comparisons (average of 3.0%) compared to control pigs. The results showed that CLA had significant effects on decreasing BF (73% of all the comparisons and all the significant comparisons) and

increasing percentage lean (81% of all the comparisons and all the significant comparisons) of grow-finish pigs. Increasing CLA concentrations did not increasingly improve the carcass characteristics. Moreover, different basal diets may affect the response to CLA on BF and percentage lean. Diets with wheat as the main ingredient had a bigger percentage of reduction in BF (13.8%; 9 comparisons) and an improvement in percentage lean (3.7%; 11 comparisons) compared to diets with corn as the main ingredient [BF decrease 7.4% (37 comparisons) and percentage lean increased 2.3% (16 comparisons)]. These results suggest that CLA has the potential to reduce BF and increase percentage lean more consistently compared to other feed additives considered in this review.

Table A.18. Studies on the effects of dietary CLA on carcass characteristics.

Author	Country	Inclusion, %	Sig.[1]	Difference, %[1]			
				Yield	BF	percentage lean	LMA/LD
Dugan et al. (1997)	Canada	1.00	percentage lean	n/a	n/a	2.3	n/a
Ostrowska et al. (1999)	Australia	0.07	percentage lean[2]	n/a	n/a	0.7	n/a
		0.14		n/a	n/a	6.0	n/a
		0.28		n/a	n/a	7.2	n/a
		0.41		n/a	n/a	5.4	n/a
		0.55		n/a	n/a	9.1	n/a
O'Quinn et al. (2000)	USA	0.30	ns	-1.4	-5.2	0.4	-4.1
Bee (2001)	Switzerland	1.20	BF	n/a	-20.7	-0.4	1.4
Dugan et al. (2001)	Canada	0.16[4]	percentage lean	n/a	n/a	6.0	n/a
		0.33[4]	percentage lean	n/a	n/a	4.4	n/a
		0.16[4]	ns	n/a	n/a	-0.3	n/a
		0.33[4]	ns	n/a	n/a	1.8	n/a
Eggert et al. (2001)	USA	0.60	ns	-0.1	-8.2	n/a	-2.0
Thiel-Cooper et al. (2001)	USA	0.07	BF	n/a	-18.2	n/a	6.4
		0.15	BF	n/a	-18.2	n/a	2.0
		0.30	ns	n/a	-8.7	n/a	-2.8
		0.60	ns	n/a	-10.1	n/a	-4.7
Wiegand et al. (2001)	USA	0.75	BF	n/a	-7.0	n/a	4.9
Averette Gatlin et al. (2002)	USA	0.60	ns	n/a	-2.6	-0.4	-2.9
Barowicz et al. (2002)	Poland	1.20	ns	-0.9	18.0	5.4	n/a
		1.20	ns	-0.1	-5.3	1.2	n/a
Dunshea et al. (2002), Exp 1	Australia	0.22	BF	0.2	-8.0	n/a	n/a
Dunshea et al. (2002), Exp 2	Australia	0.22	ns	0.7	1.0	n/a	n/a
Tischendorf et al. (2002)	Germany	1.08	percentage lean	-0.4	-7.4	2.6	n/a
Wiegand et al. (2002)	USA	0.75[5]	BF[2], percentage lean[2], LMA[2]	n/a	-14.5	5.0	6.6
		0.75[5]		n/a	-14.5	6.4	11.0
		0.75[5]		n/a	-20.6	7.4	9.2

Corino et al. (2003)	Italy	0.16	BF[3]	0.0	-12.8	n/a	n/a
		0.33	BF[3]	-0.1	-8.9	n/a	n/a
Ostrowska et al. (2003)	Australia	0.07	ns[2]	-1.3	n/a	n/a	n/a
		0.14		-0.6	n/a	n/a	n/a
		0.28		-0.3	n/a	n/a	n/a
		0.41		0.1	n/a	n/a	n/a
		0.55		-2.3	n/a	n/a	n/a
Sun et al. (2004)	China	1.36	BF[2], LMA[2]	n/a	-8.6	n/a	4.6
		2.72		n/a	-10.4	n/a	5.7
Barowicz et al. (2005)	Poland	1.20	BF, LMA	-1.0	-9.5	3.0	8.5
Corino et al. (2005)	Italy	0.38	ns	-1.7	1.8	n/a	n/a
Lauridsen et al. (2005)	Denmark	0.30	ns	n/a	0.4	0.4	1.2
Ostrowska et al. (2005)	Australia	0.07	BF[2]	-1.3	-7.1	n/a	n/a
		0.14		-0.6	-17.8	n/a	n/a
		0.28		-0.3	-17.4	n/a	n/a
		0.41		0.1	-19.1	n/a	n/a
		0.55		-2.3	-23.7	n/a	n/a
Rossi et al. (2005)	Italy	0.38	ns	0.2	n/a	0.4	n/a
Weber et al. (2006)	USA	0.60	BF[3], percentage lean, LMA[3]	-0.6	-7.0	1.8	3.7
Bee et al. (2008)	Switzerland	0.60	BF	n/a	-11.0	0.9	n/a
Corino et al. (2008)	Italy	0.38	ns	-0.8	0.4	-0.4	-3.7
Martin et al. (2008)	Spain	0.56	ns	-0.5	0.0	n/a	n/a
		1.12	ns	-0.2	5.2	n/a	n/a
Cechova et al. (2009)	Czech Republic	1.20	ns	n/a	1.2	n/a	-2.6
Larsen et al. (2009)	USA	0.45	ns	n/a	-6.1	n/a	4.4
White et al. (2009)	USA	0.60	ns	n/a	3.6	2.4	-0.4
Cechova et al. (2010)	Czech Republic	1.20	ns	n/a	n/a	-0.6	n/a
Cordero et al. (2010)	Spain	0.60	ns	-0.9	-2.7	n/a	n/a
Cordero et al. (2010)	Spain	0.30	ns[2]	-1.5	n/a	n/a	n/a
		0.60		-0.8	n/a	n/a	n/a
		1.20		0.1	n/a	n/a	n/a
Jiang et al. (2010)	China	1.00	BF, percentage lean	-0.2	-26.8	4.7	9.3

		2.00	BF	-0.5	-8.5	3.5	-2.0
Han et al. (2011)	China	0.36	Yield[2,3]	3.0	n/a	n/a	n/a
		0.71		3.7	n/a	n/a	n/a
		1.09		2.3	n/a	n/a	n/a
Lee et al. (2011)	South Korea	0.59	ns	-1.9	-2.7	n/a	n/a
Barnes et al. (2012)	USA	0.60	BF, LMA	n/a	-16.0	1.8	-5.9
Go et al. (2012)	USA	0.80	ns	0.5	-1.5	n/a	-0.5
Martinez-Aispuro et al. (2012)	Mexico	--	ns	n/a	1.6	-1.8	-7.5
Rickard et al. (2012)	USA	0.36	BF, LMA	n/a	-12.7	n/a	-4.8
Pompeu et al. (2013)	USA	0.60[4]	Yield, BF[3]	-1.0	-3.0	0.9	2.4
		0.60[4]	Yield, BF[3]	-0.6	-0.9	0.2	0.1
Tous et al. (2013)	Spain	2.51	ns	-0.6	-11.6	5.0	0.8
Bothma et al. (2014)	South Africa	0.15	ns	n/a	-4.0	n/a	n/a
		0.30	ns	n/a	-1.0	n/a	n/a
		0.60	ns	n/a	-14.0	n/a	n/a
Martínez-Aispuro et al. (2014)	Mexico	0.60	ns	n/a	-5.8	-0.3	-4.3
Wang et al. (2015)	China	0.60	ns	3.1	0.0	n/a	5.2
Marcolla et al. (2017)	Brazil	0.28[4]	BF	0.0	-27.5	n/a	2.0
		0.28[4]	ns	-0.2	5.8	n/a	-4.2
Upadhaya et al. (2017)	South Korea	0.28	ns	n/a	-2.3	1.0	0.9
		0.56	ns	n/a	-6.4	1.8	0.9
Panisson et al. (2020)	Brazil	0.18	ns	n/a	4.8	n/a	-0.3
		0.36	ns	n/a	5.2	n/a	-3.6

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[5]CLA was fed in the 3 treatment diets during the last 29, 56, or 87 kg of BW gain before slaughter respectively.

4. L-carnitine

There were 12 research articles for L-carnitine with 29 comparisons from 4 countries during the grow-finish or finishing period with added dietary levels of 25 to 250 mg/kg, with most studies feeding 50 mg/kg. Of these, 24 comparisons reported growth performance data, and 22 comparisons reported carcass data.

4.1. Growth Performance – L-carnitine

Average daily gain significantly increased ($P \leq 0.05$) in 2 comparisons (average of 3.3%), tended to increase ($0.05 < P \leq 0.10$) in 4 comparisons (average of 3.1%), and significantly decreased ($P \leq 0.05$) in 1 comparison (4.8%) compared to control pigs (Table A.19). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (17 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 13 comparisons (average of 3.4%) and numerically decreased ($P > 0.10$) in 3 comparisons (average of 2.6%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 1 comparison (2.9%) and tended to increase ($0.05 < P \leq 0.10$) in 3 comparisons (average of 3.7%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (20 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 13 comparisons (average of 4.4%) and numerically decreased ($P > 0.10$) in 5 comparisons (average of 2%) compared to control pigs. Overall, the results suggest that L-carnitine has the potential to improve ADG and G:F (79 and 71% of all the comparisons) with relatively large improvement.

Moreover, the beneficial effects of L-carnitine were significant ($P < 0.10$) for ADG and G:F in 25 and 23% of all the comparisons, respectively. There were not enough data to support whether different inclusion levels or types of basal diets affected the response to L-carnitine for ADG and G:F. However, results might suggest that pigs fed L-carnitine were more likely to have improved ADG and G:F when fed in diets without DDGS [290-292], but further research is needed to confirm this. Additionally, environmental factors, such as temperature, humidity, and stress level, may affect L-carnitine response [293] due to the change in feed intake and physiological status.

Table A.19. Studies on the effects of dietary L-carnitine on growth performance.

Authors	Country	Inclusion, mg/kg	Sig.[1]	Difference, %[1]	
				ADG	G:F
Owen et al. (2001)	USA	50	ns[2]	2.2	-3.1
		125		-1.1	0.0
Owen et al. (2001)	USA	25	ns[2]	3.3	3.1
		50		2.2	6.3
		75		3.3	6.3
		100		6.5	6.3
		125		2.2	6.3
Waylan et al. (2003)	USA	50	ns	0.8	1.3
Bertol et al. (2005)	USA	150	ns	-4.7	-3.6
Han and Thacker (2006)	South Korea	50	ns	5.0	7.1
Chen et al. (2008)	South Korea	250	ns	3.9	3.1
Pietruszka et al. (2009)	Poland	100	ns	1.4	1.2
James et al. (2013)	USA	50	ns	0.0	-0.4
James et al. (2013), Exp. 1	USA	25	ADG[2]	-4.8	0.0
		50		0.6	-1.6
James et al. (2013), Exp. 2	USA	25	G:F[2,3]	2.3	5.5
		50		-1.9	4.1
James et al. (2013), Exp. 3	USA	50	ns	9.4	7.7
James et al. (2013), Exp. 4	USA	50	ADG, G:F	6.0	2.9
Ying et al. (2013)	USA	50[4]	ADG[2,3]	4.9	3.5
		100[4]		3.7	0.6
		50[4]	ADG[2,3]	2.4	-1.2
		100[4]		1.2	4.2
Meng et al. (2018)	USA	50	G:F[3]	1.8	1.5

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]The basal diets were corn-SBM based in the top two comparisons. The basal diets were corn-DDGS-SBM based in the bottom two comparisons.

4.2. Carcass Characteristics – L-carnitine

Back-fat significantly increased ($P \leq 0.05$) in 3 comparisons (average of 4%), tended to increase ($0.05 < P \leq 0.10$) in 2 comparisons (average of 1.4%), significantly decreased ($P \leq 0.05$) in 2 comparisons (average of 12.5%), and tended to decrease ($0.05 < P \leq 0.10$) in 7 comparisons (average of 4.8%) compared to control pigs (Table A.20). Eight comparisons found no evidence of difference ($P > 0.10$) in BF. Of these, BF was numerically increased ($P > 0.10$) in 1 comparison (1.9%) and numerically decreased ($P > 0.10$) in 6 comparisons (average of 5.7%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in 4 comparisons (average of 3.8%), tended to increase ($0.05 < P \leq 0.10$) in 2 comparisons (average of 1.5%), and significantly decreased ($P \leq 0.05$) in 3 comparisons (average of 1.3%) compared to control pigs. Half of the studies found no evidence of difference ($P > 0.10$) in percentage lean (11 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 7 comparisons (average of 1.5%) and numerically decreased ($P > 0.10$) in 3 comparisons (average of 0.7%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 1 comparison (6.3%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (20 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 13 comparisons (average of 4.4%) and numerically decreased ($P > 0.10$) in 6 comparisons (average of 2.3%) compared to control pigs. There were not enough data to support whether different inclusion levels or types of basal diets affected the response to L-carnitine for carcass

characteristics. Overall, the results suggest that L-carnitine is a potential feed additive that had relatively large positive effects on BF, percentage lean, and LMA/LD (68, 65, and 67% of all the comparisons) compared to other feed additives in this review, with 23, 30, and 5% of all the comparisons being significant ($P < 0.10$), respectively.

Table A.20. Studies on the effects of dietary L-carnitine on carcass characteristics.

Authors	Country	Inclusion, mg/kg	Sig.[1]	Difference, %[1]			
				Yield	BF	percentage lean	LMA/LD
Owen et al. (2001)	USA	50	BF[2,3], percentage lean[2]	-1.3	-2.6	1.8	1.4
		125		-1.2	-4.3	4.1	9.2
Owen et al. (2001)	USA	25	BF[2,3], percentage lean[2]	0.9	0.6	-2.6	-6.4
		50		-0.4	-9.1	7.6	12.6
		75		-0.7	-5.0	1.9	0.2
		100		-0.1	-2.8	-0.3	-1.1
		125		1.0	2.2	-0.9	0.6
Waylan et al. (2003)	USA	50	ns	0.5	1.9	0.1	2.2
Bertol et al. (2005)	USA	150	ns	n/a	-3.8	n/a	-2.2
Han and Thacker (2006)	South Korea	50	ns	-0.1	-10.5	0.8	n/a
Chen et al. (2008)	South Korea	250	BF	n/a	-18.2	1.8	16.2
Pietruszka et al. (2009)	Poland	100	ns	2.7	-7.4	1.4	-3.4
James et al. (2013), Exp.1	USA	25	ns[2]	-0.6	-3.1	2.2	1.8
		50		-0.7	-2.2	1.7	0.2
James et al. (2013), Exp.2	USA	25	BF[2,3], percentage lean[2,3]	3.0	-2.0	1.2	7.5
		50		0.6	-7.6	1.7	2.0
James et al. (2013), Exp.3	USA	50	LMA	n/a	-7.1	2.4	6.3
Ying et al. (2013)[7]	USA	50[4]	Yield[2,3], BF[2]	1.6	4.8	-0.7	0.5
		100[4]		0.4	3.0	-0.5	-0.3
		50[4]	Yield[2,3], BF[2]	0.3	4.2	-0.7	-0.3
		100[4]		0.1	0.0	0.0	0.0
Meng et al. (2018)	USA	50	BF	-0.2	-6.7	n/a	3.3

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]The basal diets were corn-SBM based in the top two comparisons. The basal diets were corn-DDGS-SBM based in the bottom two comparisons.

Feed Additives – Enzymes

This section discusses dietary enzymes used as feed additives in classes of carbohydrases, proteases, phytases, and combination of different types of enzymes (multi-enzymes). There were 86 research articles for enzymes with 165 comparisons from 13 countries during the grow-finish or finishing period which met the requirements for inclusion. Of these, 163 comparisons reported growth performance data, and 107 comparisons reported carcass data. For phytases, its effect in low P diets has been well established, thus, only experiments that utilized diets at/above P requirement were included to discuss the other potential benefits of adding phytases.

1. *Growth performance - Carbohydrases*

Average daily gain significantly increased ($P \leq 0.05$) in 15 comparisons (average of 5.3%), tended to increase ($0.05 < P \leq 0.10$) in 5 comparisons (average of 4%), and significantly decreased ($P \leq 0.05$) in 4 comparisons (average of 2.7%) compared to control pigs (Table A.21). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (63 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 35 comparisons (average of 2.9%) and numerically decreased ($P > 0.10$) in 24 comparisons (average of 3.3%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 8 comparisons (average of 8.5%) and tended to increase ($0.05 < P \leq 0.10$) in 2 comparisons (average of 5.9%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (74 comparisons). Of these, G:F was numerically

increased ($P > 0.10$) in 46 comparisons (average of 2.9%) and numerically decreased ($P > 0.10$) in 19 comparisons (average of 3.8%) compared to control pigs. Overall, the results suggest that carbohydrases had positive effects on ADG and G:F (63 and 67% of all the comparisons), but the magnitude was small, and most comparisons had no statistical differences. Additionally, in a meta-analysis conducted by Aranda-Aguirre et al. [302], the authors found that β-mannanase and xylanase had no effects ($P > 0.10$) on growth performance of finishing pigs. However, in another meta-analysis by Kiarie et al. [303], the authors found β-mannanase improved ($P < 0.0001$) ADG and G:F of grow-finish pigs. Dietary composition and differences in primary ingredients utilized may affect the effect of carbohydrases on ADG and G:F. Corn diets (32 comparisons) had 2.6% improvement in ADG and 2.2% increase in G:F; Barley diet had 0.4% improvement in ADG (23 comparisons) and 1.7% improvement in G:F (21 comparisons); and wheat diet had 0.9% decrease in ADG (16 comparisons) and 0.2% improvement in G:F (15 comparisons). Moreover, with the limited data, carbohydrases appeared to improve ADG and G:F in some trials with diets that were low in energy and/or AAs, which suggest carbohydrases may be beneficial for the economic efficiency in diets formulated below requirements. Moreover, carbohydrases showed no benefit or negative effects in diets with high level of DDGS (above 15%). Because the production of DDGS utilizes carbohydrases during the fermentation stage to release the nutrients (starch), there may not be enough available substrates for dietary carbohydrases to be beneficial.

Table A.21. Studies on the effects of enzymes on growth performance.

Author	Country	Enzyme	Sig.[1]	Difference, %[1] ADG	G:F
Thacker et al. (1988)	Canada	Carbohydrases	ns	2.7	0.6
Thacker et al. (1992)	Canada	Carbohydrases[5]	ns	1.2	1.6
			ns	-8.1	-3.7
Baas and Thacker (1996)	Canada	Carbohydrases[a]	ns	0.0	2.4
		Carbohydrases[b]	ns	-3.5	2.9
		Carbohydrases[c]	ns	-1.2	1.6
		Carbohydrases[d]	ns	-3.5	0.8
Kim et al. (1998)	USA	Carbohydrases	ns	3.2	-0.4
Flis et al. (1998)	Poland	Carbohydrases[5]	ns	3.1	3.3
			ns	4.4	4.7
O'Doherty and Forde (1999)	Ireland	Carbohydrases	ns	-2.6	0.3
Thacker and Campbell (1999)	Canada	Carbohydrases[5]	ns	0.0	0.0
			ns	-2.1	2.4
Mavromichalis et al. (2000), Exp. 1	USA	Carbohydrases	ns	-1.7	3.5
Mavromichalis et al. (2000), Exp. 2	USA	Carbohydrases	ns	2.2	0.0
Grandhi (2001)	Canada	Carbohydrases	G:F	1.2	4.2
Pettey et al. (2002)	USA	Carbohydrases	ADG, G:F[3]	3.6	4.2
Park et al. (2003), Exp. 1	USA	Carbohydrases	ns	2.2	2.7
Park et al. (2003), Exp. 2	USA	Carbohydrases[4]	ADG[2,3]	4.4	2.8
				3.3	2.8
				6.7	5.6
Park et al. (2003), Exp. 3	USA	Carbohydrases[4]	ns[2]	0.0	0.0
				1.1	3.1
				1.1	0.0
Park et al. (2003)	USA	Carbohydrases[5]	ns	2.2	5.9
			ns	-5.4	-4.7
			ns	-5.8	-5.4
			ns	1.6	1.0
			ns	-2.9	-0.5
Flis and Sobotka (2005)	Poland	Carbohydrases	ns	2.6	3.2
Thacker (2005), Exp. 1	Canada	Carbohydrases	ns	0.0	1.1
Thacker (2005), Exp. 2	Canada	Carbohydrases	ns	-1.9	0.0
Thacker and Rossnagel (2005)	Canada	Carbohydrases[5]	ns	3.9	3.1
			ns	-1.9	-3.7
			ns	-1.9	0.0
Thacker and Rossnagel (2005)	Canada	Carbohydrases[5]	ns	1.9	1.6
			ns	1.8	2.9
			ns	1.8	0.4
Kim et al. (2006)	USA	Carbohydrases[6]	G:F[3]	14.8	7.7
			G:F[3]	0.8	0.0

Roșu and Falcă (2007)	Romania	Carbohydrases	ns	6.5	9.4
Świątkiewicz and Hanczakowska (2008)	Poland	Carbohydrases[5]	ns	1.7	n/a
			ns	4.6	n/a
Wang et al. (2009)	South Korea	Carbohydrases[a]	ADG, G:F	9.6	14.3
		Carbohydrases[b]	ADG, G:F	8.4	16.5
Widyaratne et al. (2009)	Canada	Carbohydrases[5]	ns	-2.9	2.8
			ns	-1.1	-9.7
Jacela et al. (2010), Exp. 1	USA	Carbohydrases	ns	0.5	-0.6
Jacela et al. (2010), Exp. 4	USA	Carbohydrases	ns	-1.0	0.0
Yoon et al. (2010), Exp. 1[4]	South Korea	Carbohydrases	ADG[2]	0.4	1.1
				4.7	5.2
				2.6	2.1
Yoon et al. (2010), Exp. 2	South Korea	Carbohydrases[5]	ADG	4.1	8.5
			ADG	2.5	1.5
Barnes et al. (2011)	USA	Carbohydrases[5]	ADG	-0.9	1.7
			ADG	-1.4	-1.4
			ADG	-1.3	-1.0
Hanczakowska et al. (2012)	Poland	Carbohydrases[4]	ns	1.5	1.9
			ADG	4.2	3.2
			ADG, G:F	6.2	10.6
Jo et al. (2012), Exp. 1	South Korea	Carbohydrases[a]	ns	1.5	1.5
		Carbohydrases[b]	ADG	2.8	3.0
McAlpine et al. (2012)	Ireland	Carbohydrases	ADG	-7.2	n/a
Cho and Kim (2013)	South Korea	Carbohydrases[a]	ns	9.9	2.4
		Carbohydrases[b]	ADG, G:F	14.7	11.9
Kerr et al. (2013)	USA	Carbohydrases[a]	ns	5.2	-2.4
		Carbohydrases[b]	ns	-6.6	-12.3
		Carbohydrases[c]	ns	-2.0	-4.5
		Carbohydrases[d]	ns	-9.3	-9.3
		Carbohydrases[e]	ns	-2.4	-3.6
Kim et al. (2013)	South Korea	Carbohydrases[a]	ADG	10.3	8.2
		Carbohydrases[b]	ns	3.8	1.9
Lipiński et al. (2013)	Poland	Carbohydrases[4]	ADG	2.6	2.1
			ADG	3.0	2.9
O'Shea et al. (2014)	Ireland	Carbohydrases	ns	-7.3	-4.9
Villca et al. (2016)	Switzerland	Carbohydrases	ns	1.5	2.5
Lindemann (2016)	USA	Carbohydrases	ns	1.0	2.3
Nguyen et al. (2018)	South Korea	Carbohydrases	ADG[3], G:F	3.4	2.7
Torres-Pitarch et al. (2018)	Ireland	Carbohydrases	ns	0.3	0.0
Smit et al. (2019)	Canada	Carbohydrases	ADG3	2.0	2.4
Jang et al. (2020)	South Korea	Carbohydrases	ns	3.2	6.8
Jang et al. (2020)	South Korea	Carbohydrases	ns	1.7	-0.3
Torres-Pitarch et al. (2020)	Ireland	Carbohydrases[5]	G:F	3.1	5.2
			G:F	-1.2	2.3
Torres-Pitarch et al. (2020)	Ireland	Carbohydrases[5]	ns	-1.9	0.4
			ns	2.3	-1.1

Kpogo et al. (2021)	Canada	Carbohydrases	ns	-0.9	-2.6
O'Doherty and Forde (1999)	Ireland	Proteases	ns	0.5	2.4
Thacker (2005), Exp. 2	Canada	Proteases	ns	-3.9	-0.4
Reyna et al. (2006)[4]	Mexico	Proteases	ns	-8.2	-4.3
			ns	-4.2	-4.3
			ns	-1.5	-2.0
McAlpine et al. (2012)	Ireland	Proteases	ADG	-5.4	n/a
O'Shea et al. (2014)	Ireland	Proteases	ADG	-9.8	0.8
Stephenson et al. (2014)	USA	Proteases	ADG[3]	1.7	-0.7
Upadhaya et al. (2016)	South Korea	Proteases	G:F	3.2	2.6
Choe et al. (2017)	South Korea	Proteases	ADG, G:F	6.0	15.1
Lei et al. (2017)	South Korea	Proteases	G:F	2.2	6.5
Nguyen et al. (2018)	South Korea	Proteases[a]	ns	2.4	2.9
		Proteases[b]	ns	1.7	2.1
Figueroa et al. (2019)	Mexico	Proteases	ns	2.9	-2.2
Liu et al. (2019)[4]	South Korea	Proteases	ADG[2,3], G:F[2]	1.8	1.0
				5.5	3.1
				3.9	1.5
Min et al. (2019)	South Korea	Proteases	ADG	5.2	2.8
Lee et al. (2020)	South Korea	Proteases	G:F[3]	4.3	7.6
Kim et al. (2021)	South Korea	Proteases[a]	ns	1.3	0.0
		Proteases[b]	ADG, G:F	4.4	4.9
Perez-Palencia et al. (2021)	USA	Proteases	ns	-0.7	-0.2
Cromwell et al. (1993), Exp. 1	USA	Phytases	ns	4.6	6.0
Cromwell et al. (1993), Exp. 2	USA	Phytases	ns	1.1	-0.3
Cromwell et al. (1995)	USA	Phytases	ns	1.6	-2.1
Helander and Partanen (1997)	Finland	Phytases	ns	-1.7	-4.5
O'Doherty et al. (1999)	Ireland	Phytases[4]	ns	1.3	0.0
			ns	1.8	2.0
Gebert et al. (1999)	Switzerland	Phytases	ADG, G:F	10.6	8.2
Gagné et al. (2002)	Canada	Phytases	ns	-4.6	1.9
Brady et al. (2002)	Ireland	Phytases	ns	5.6	1.5
Thacker and Rossnagel (2006)	Canada	Phytases	ns	2.5	-3.2
Thacker et al. (2006)	Canada	Phytases	ns	5.2	3.3
Varley et al. (2010), Exp. 1	Ireland	Phytases	ns	4.2	1.6
Varley et al. (2010), Exp. 2	Ireland	Phytases	ns	-3.0	0.0
Kerr et al. (2013)	USA	Phytases	ns	-3.8	-6.6
Langbein et al. (2013)	USA	Phytases [a]	ns	-3.3	0.3
		Phytases [b]	ns	-2.3	-0.3
		Phytases [c]	ns	-2.3	-0.3
Patience (2015)	USA	Phytases[4]	ns	1.6	0.0
			ns	0.0	0.0
			ns	1.6	0.0
Pérez Alvarado et al. (2015)	Mexico	Phytases [a]	ns	0.0	6.9
		Phytases [b]	ns	-3.0	2.3
Lindemann (2016)	USA	Phytases[4]		7.5	2.9

			ADG[2],	8.8	5.0
			G:F[2,3]	5.5	5.9
Holloway et al. (2019)	USA	Phytases[4]	ns	1.5	0.9
			ns	0.1	1.2
			ns	1.3	1.2
Dang and Kim (2021)	South Korea	Phytases	ADG, G:F	5.7	3.3
Dang and Kim (2021)	South Korea	Phytases	ADG, G:F[3]	4.1	2.9
Baas and Thacker (1996)	Canada	Multi-enzymes	ns	-2.3	2.4
Thacker (2005), Exp. 2	Canada	Multi-enzymes	ns	-2.9	0.4
Domaćinović et al. (2006)	Croatia	Multi-enzymes[5]	ns	0.7	0.3
			ns	1.6	1.3
Feoli et al. (2008)	USA	Multi-enzymes	ns	-0.3	-2.1
Benz et al. (2009)	USA	Multi-enzymes	ns	0.5	1.9
Thacker (2009)	Canada	Multi-enzymes	ns	5.7	2.8
Thacker and Haq (2009)	Canada	Multi-enzymes	ns	-1.2	0.7
Jacela et al. (2010), Exp. 2	USA	Multi-enzymes	ns	-0.1	-0.8
Jacela et al. (2010), Exp. 3	USA	Multi-enzymes[a]	ns	1.7	0.0
		Multi-enzymes[b]	ns	0.1	0.0
Ao et al. (2011)	South Korea	Multi-enzymes[4]	ADG[2], G:F[2]	6.3	2.8
				7.6	5.6
Lee et al. (2011)	South Korea	Multi-enzymes	G:F	2.3	9.2
Jo et al. (2012), Exp. 1	South Korea	Multi-enzymes[a]	ADG	3.2	3.4
		Multi-enzymes[b]	ADG, G:F	5.0	4.9
Jo et al. (2012), Exp. 2	South Korea	Multi-enzymes	ADG, G:F	2.9	3.6
Kerr et al. (2013)	USA	Multi-enzymes	ns	-1.6	-6.6
Sitanaka et al. (2018)	Brazil	Multi-enzymes	ns	8.3	0.8
			ADG, G:F	24.9	11.2
			ns	0.8	3.8
			ns	7.2	1.3
Lawlor et al. (2019)	Ireland	Multi-enzymes	ADG, G:F	11.3	2.6
Balasubramanian et al. (2020)	South Korea	Multi-enzymes	ADG, G:F	8.5	16.9
Coelho et al. (2020)	Portugal	Multi-enzymes[a]	ns	-6.5	-5.5
		Multi-enzymes[b]	ns	-3.7	-1.5
Jerez-Bogota et al. (2020)	USA	Multi-enzymes[5]	G:F	0.0	30.8
			ADG	5.6	2.4
Huang et al. (2021)	China	Multi-enzymes	G:F	4.0	2.6

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]Same enzyme of each experiment was used with different inclusion levels. The inclusion level of each comparison increases from top to bottom.

[5]For experiments using factorial treatment structures, if the interaction of factors of either interested variable

was observed the effect of the feed additive within each level of the other factor is included within the database.

[6]The top comparison was the result of barrow and the bottom comparison was the results of gilts.
[a,b,c,d] Enzyme compositions within an experiment with different superscripts differ.

2. *Carcass Characteristics - Carbohydrases*

Back-fat significantly increased ($P \leq 0.05$) in 2 comparisons (average of 4.1%) and tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (4.8%) compared to control pigs (Table A.22). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (54 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 18 comparisons (average of 4.0%) and numerically decreased ($P > 0.10$) in 29 comparisons (average of 3.7%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in 1 comparison (5.6%) and significantly decreased ($P \leq 0.05$) in 2 comparisons (average of 0.7%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (52 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 28 comparisons (average of 1.1%) and numerically decreased ($P > 0.10$) in 20 comparisons (average of 0.8%) compared to control pigs. All studies found no evidence of difference ($P > 0.10$) in LMA/LD (38 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 20 comparisons (average of 3.3%) and numerically decreased ($P > 0.10$) in 17 comparisons (average of 1.5%) compared to control pigs.

Table A.22. Studies on the effects of enzymes on carcass characteristics.

Author	Country	Enzyme	Sig.[1]	Difference, %[1]			
				Yield	BF	percentage lean	LMA/LD
Thacker et al. (1992)	Canada	Carbohydrases[5]	ns	0.9	n/a	-1.0	n/a
			ns	-0.3	n/a	-0.2	n/a
Kim et al. (1998)	USA	Carbohydrases	ns	0.6	-3.1	0.9	n/a
O'Doherty and Forde (1999)	Ireland	Carbohydrases	ns	-0.6	2.7	-0.5	0.1
Thacker and Campbell (1999)	Canada	Carbohydrases[5]	ns	1.7	0.5	0.2	-0.7
			ns	-0.4	-1.4	0.0	-2.7
Mavromichalis et al. (2000), Exp.1	USA	Carbohydrases	ns	0.1	-2.2	0.2	n/a
Mavromichalis et al. (2000), Exp.2	USA	Carbohydrases	ns	-0.1	-1.2	0.1	n/a
Grandhi (2001)	Canada	Carbohydrases	ns	0.1	-0.7	n/a	n/a
Pettey et al. (2002)	USA	Carbohydrases	ns	n/a	-4.9	1.9	5.9
Park et al. (2003), Exp.1	USA	Carbohydrases	ns	-0.3	0.4	-0.4	n/a
Park et al. (2003), Exp.2	USA	Carbohydrases[4]	ns[2]	2.6	-5.1	1.5	n/a
				0.4	-1.6	0.4	n/a
				0.7	-3.5	0.9	n/a
Park et al. (2003), Exp.3	USA	Carbohydrases[4]	ns[2]	-0.5	-1.6	0.2	n/a
				-2.9	-4.4	0.6	n/a
				0.0	-2.7	0.6	n/a
Park et al. (2003)	USA	Carbohydrases[5]	ns	-1.2	2.1	-0.2	n/a
			ns	-0.1	-6.9	1.6	n/a
			ns	-0.1	-7.6	2.0	n/a
			ns	-0.3	2.8	-0.4	n/a
			ns	-1.2	0.0	0.0	n/a
Flis and Sobotka (2005)	Poland	Carbohydrases	ns	n/a	n/a	-0.1	n/a
Thacker (2005), Exp. 2	Canada	Carbohydrases	ns	0.0	-5.3	0.7	-3.1
Thacker and Rossnagel (2005)	Canada	Carbohydrases[5]	ns	0.9	0.0	-0.3	-3.5
			ns	0.9	-1.6	0.3	3.1

			ns	-0.1	-2.1	0.0	1.6
Thacker and Rossnagel (2005)	Canada	Carbohydrases[5]	ns	0.5	-1.2	0.0	1.0
			ns	0.1	-5.9	0.8	3.2
			ns	0.9	-1.8	-0.2	-2.8
Świątkiewicz and Hanczakowska (2008)	Poland	Carbohydrases[5]	ns	8.1	-2.5	0.9	n/a
			ns	8.3	-1.9	-0.7	n/a
Wang et al. (2009)	South Korea	Carbohydrases[a]	ns	n/a	0.8	0.7	6.5
		Carbohydrases[b]	ns	n/a	2.5	1.1	9.8
Yoon et al. (2010), Exp. 1[4]	South Korea	Carbohydrases	ns[2]	1.0	-0.6	0.8	1.1
				0.2	-2.5	1.8	2.3
				0.3	-1.9	1.2	1.4
Yoon et al. (2010), Exp. 2	South Korea	Carbohydrases[5]	ns	4.0	16.1	-4.8	-2.6
			ns	1.8	6.7	8.1	12.7
Barnes et al. (2011)	USA	Carbohydrases[5]	ns	0.8	0.0	0.2	0.0
			ns	-1.5	-1.2	-0.4	-3.0
			ns	0.0	0.0	0.8	2.6
Pauly et al. (2011)	Ireland	Carbohydrases[5]	ns	-1.8	6.0	-1.0	n/a
			percentage lean	5.1	-17.0	5.6	n/a
Hanczakowska et al. (2012)	Poland	Carbohydrases[4]	ns	-0.2	-6.0	-0.4	-0.3
			ns	-0.3	0.0	-0.7	-0.3
			ns	0.2	0.5	0.6	0.1
Cho and Kim (2013)	South Korea	Carbohydrases[a]	ns	n/a	2.1	n/a	4.1
		Carbohydrases[b]	ns	n/a	3.4	n/a	5.1
O'Shea et al. (2014)	Ireland	Carbohydrases	ns	-0.4	-6.3	1.5	n/a
Lindemann (2016)	USA	Carbohydrases	ns	n/a	0.1	-0.1	-1.1
Villca et al. (2016)	Switzerland	Carbohydrases	ns	-0.1	-0.7	-0.2	-0.9
Nguyen et al. (2018)	South Korea	Carbohydrases	ns	n/a	n/a	n/a	0.1
Torres-Pitarch et al. (2018)	Ireland	Carbohydrases	ns	0.0	0.0	0.5	-0.2

Smit et al. (2019)	Canada	Carbohydrases	ns	0.3	0.0	0.2	0.8
Jang et al. (2020)	South Korea	Carbohydrases	ns	-0.2	-5.5	n/a	n/a
Torres-Pitarch et al. (2020)	Ireland	Carbohydrases[5]	ns	-0.5	6.2	-0.5	3.2
			ns	0.4	1.7	-0.3	-0.6
Torres-Pitarch et al. (2020)	Ireland	Carbohydrases[5]	BF, percentage lean	0.3	1.6	-0.2	-1.2
			BF, percentage lean	0.0	6.6	-1.2	-0.8
Kpogo et al. (2021)	Canada	Carbohydrases	BF[3]	0.2	4.8	n/a	-1.0
O'Doherty and Forde (1999)	Ireland	Proteases	ns	0.2	10.8	-2.1	-4.0
Thacker (2005), Exp. 2	Canada	Proteases	ns	0.4	-8.3	1.5	5.4
Reyna et al. (2006)	Mexico	Proteases[4]	ns	n/a	n/a	-1.2	-6.1
			ns	n/a	n/a	-1.1	-5.6
			ns	n/a	n/a	-1.9	-6.5
O'Shea et al. (2014)	Ireland	Proteases	ns	-0.4	-4.0	0.4	n/a
Stephenson et al. (2014)	USA	Proteases	Yield	-1.2	0.0	0.0	0.8
Choe et al. (2017)	South Korea	Proteases	Yield[3]	0.2	-2.7	-0.2	n/a
Torres-Pitarch et al. (2018)	Ireland	Proteases	ns	-0.7	0.8	-0.3	-2.0
Figueroa et al. (2019)	Mexico	Proteases	ns	n/a	1.9	n/a	-0.7
Liu et al. (2019)	South Korea	Proteases[4]	BF[2,3]	n/a	1.1	0.7	n/a
				n/a	6.2	2.4	n/a
				n/a	3.7	0.9	n/a
Min et al. (2019)	South Korea	Proteases	ns	-0.4	-5.4	n/a	n/a
Lee et al. (2020)	South Korea	Proteases	ns	-0.1	-4.2	n/a	n/a
Perez-Palencia et al. (2021)	USA	Proteases	ns	n/a	-1.7	0.4	1.1
Helander and Partanen (1997)	Finland	Phytases	ns	-1.7	n/a	n/a	n/a
O'Doherty et al. (1999)4	Ireland	Phytases[4]	ns	1.1	-6.5	1.3	0.9
			ns	3.1	0.0	-0.2	3.5
Brady et al. (2002)	Ireland	Phytases	Yield	-1.0	2.0	-0.6	n/a
Thacker et al. (2006)	Canada	Phytases	ns	0.0	-6.7	0.0	-11.6
Thacker and Rossnagel (2006)	Canada	Phytases	ns	-0.1	2.7	-0.8	-11.3
Varley et al. (2010), Exp. 1	Ireland	Phytases	ns	0.7	-0.8	-0.2	n/a
Varley et al. (2010), Exp. 2	Ireland	Phytases	ns	-0.7	1.6	-0.5	n/a

Langbein et al. (2013)	USA	Phytases [a]	ns	0.5	1.3	0.5	3.3
		Phytases [b]	ns	0.3	0.0	0.3	2.1
		Phytases [c]	ns	0.3	1.3	0.1	1.7
Pérez Alvarado et al. (2015)	Mexico	Phytases [a]	ns	n/a	-2.6	n/a	-1.8
		Phytases [b]	ns	n/a	-4.4	n/a	-3.0
Lindemann (2016)	USA	Phytases[4]	BF[2,3],	n/a	-6.1	1.4	2.3
			percentage	n/a	-13.4	2.9	4.0
			lean[2]	n/a	-10.8	2.8	6.4
Holloway et al. (2019)	USA	Phytases[4]	ns	0.3	n/a	n/a	n/a
			ns	0.0	n/a	n/a	n/a
			ns	-0.4	n/a	n/a	n/a
Dang and Kim (2021)	South Korea	Phytases	BF	n/a	8.3	n/a	0.4
Dang and Kim (2021)	South Korea	Phytases	ns	n/a	1.2	n/a	0.3
Thacker (2005), Exp. 2	Canada	Multi-enzymes	ns	0.8	-1.0	0.2	-1.4
Domaćinović et al. (2006)	Croatia	Multi-enzymes[5]	ns	n/a	n/a	1.1	n/a
			percentage lean	n/a	n/a	4.4	n/a
Feoli et al. (2008)	USA	Multi-enzymes	ns	0.1	-1.6	0.0	-1.1
Benz et al. (2009)	USA	Multi-enzymes	ns	-0.4	-0.5	-0.4	-2.2
Thacker (2009)	Canada	Multi-enzymes	ns	-1.9	-3.9	0.2	-3.2
Thacker and Haq (2009)	Canada	Multi-enzymes	ns	0.1	11.3	-1.3	3.5
Lee et al. (2011)	South Korea	Multi-enzymes	ns	0.2	-12.3	n/a	n/a
Ao et al. (2011)	South Korea	Multi-enzymes[4]	ns[2]	n/a	1.9	0.7	0.3
				n/a	1.4	1.2	1.7
Balasubramanian et al. (2020)	South Korea	Multi-enzymes	BF	n/a	-10.2	n/a	-6.0
Coelho et al. (2020)	Portugal	Multi-enzymes[a]	ns	-0.3	29.4	n/a	n/a
		Multi-enzymes[b]	ns	-0.4	15.5	n/a	n/a

Huang et al. (2021)	China	Multi-enzymes	LMA	1.7	3.1	n/a	11.3

[1]Significant level at $P \leq 0.05$. Difference is calculated as [(treatment value – control value) / control value] * 100%.

[2]Polynomial contrasts were used for statistical analysis.

[3]Significant level at $0.05 < P \leq 0.10$.

[4]Same enzyme of each experiment was used with different inclusion levels. The inclusion level of each comparison increases from top to bottom.

[5]For experiments using factorial treatment structures, if the interaction of factors of either interested variable was observed the effect of the feed additive within each level of the other factor is included within the database.

[a,b,c] Enzyme compositions within an experiment with different superscripts differ.

3. *Growth performance - Proteases*

Average daily gain significantly increased ($P \leq 0.05$) in 3 comparisons (average of 5.2%), tended to increase ($0.05 < P \leq 0.10$) in 4 comparisons (average of 3.2%), and significantly decreased ($P \leq 0.05$) in 2 comparisons (average of 7.6%) compared to control pigs (Table A.21). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (14 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 9 comparisons (average of 2.1%) and numerically decreased ($P > 0.10$) in 5 comparisons (average of 3.7%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 7 comparisons (average of 4.9%) and tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (7.6%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (14 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 5 comparisons (average of 2.2%) and numerically decreased ($P > 0.10$) in 7 comparisons (average of 2%) compared to control pigs. Overall, the results suggest that proteases had positive effects on ADG and G:F (70 and 59% of all the comparisons), but the effects were small for ADG. Moreover, in a meta-analysis conducted by Aranda-Aguirre et al. [302], the authors found that proteases had no effects ($P > 0.10$) on growth performance of finishing pigs. There were not enough data to support whether different basal diets affected the response to proteases for ADG and G:F. The lack of substantial positive effects of exogenous proteases may be due to the high digestibility of dietary protein with the endogenous proteases of the mature grow-finish pig. Even though the digestibility of CP or N was improved ($P \leq 0.05$) in some studies [332, 345, 352, 372], the improvements may not be large enough to improve growth performance.

3.1. *Carcass Characteristics - Proteases*

Back-fat tended to increase ($0.05 < P \leq 0.10$) in 3 comparisons (average of 3.7%) compared to control pigs (Table A.22). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (10 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 3 comparisons (average of 4.5%) and numerically decreased ($P > 0.10$) in 6 comparisons (average of 4.4%) compared to control pigs. All the comparisons found no evidence of difference ($P > 0.10$) in percentage lean. Of these, percentage lean was numerically increased ($P > 0.10$) in 6 comparisons (average of 1.1%) and numerically decreased ($P > 0.10$) in 6 comparisons (average of 1.1%) compared to control pigs. All the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD. Of these, LMA/LD was numerically increased ($P > 0.10$) in 3 comparisons (average of 2.4%) and numerically decreased ($P > 0.10$) in 6 comparisons (average of 4.1%) compared to control pigs.

4. *Growth performance - Phytases*

Average daily gain significantly increased ($P \leq 0.05$) in 3 comparisons (average of 6.8%) compared to control pigs (Table A.21). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (21 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 12 comparisons (average of 2.6%) and numerically decreased ($P > 0.10$) in 8 comparisons (average of 3.0%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 2 comparisons (average of 5.7%) and tended to increase ($0.05 < P \leq 0.10$) in 1 comparison (2.9%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (21 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 13 comparisons (average of 2.3%) and numerically decreased ($P > 0.10$) in 7 comparisons (average of 2.5%) compared to control pigs. Overall, the results suggest that phytases had positive effects on ADG (63% of all comparisons) and G:F

(67% of all comparisons), but most comparisons were not statistically significant (88% of all comparisons). Moreover, in a meta-analysis conducted by Aranda-Aguirre et al. [302], the authors found that phytases had no effects ($P > 0.10$) on growth performance of finishing pigs. There was not enough data to support whether different phytase inclusion levels and basal diets affected the response to phytases for ADG and G:F in grow-finish pig diets with adequate P levels.

5. *Carcass Characteristics - Phytases*

Back-fat significantly increased ($P \leq 0.05$) in 1 comparison (8.3%) compared to control pigs (Table A.22). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (13 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 6 comparisons (average of 1.7%) and numerically decreased ($P > 0.10$) in 5 comparisons (average of 4.2%) compared to control pigs. All the comparisons found no evidence of difference ($P > 0.10$) in percentage lean. Of these, percentage lean was numerically increased ($P > 0.10$) in 4 comparisons (average of 0.6%) and numerically decreased ($P > 0.10$) in 5 comparisons (average of 0.5%) compared to control pigs. All the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD. Of these, LMA/LD was numerically increased ($P > 0.10$) in 7 comparisons (average of 1.7%) and numerically decreased ($P > 0.10$) in 4 comparisons (average of 6.9%) compared to control pigs.

6. *Growth performance - Multi-enzymes*

Average daily gain significantly increased ($P \leq 0.05$) in 10 comparisons (average of 7.9%) compared to control pigs (Table A.21). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in ADG (19 comparisons). Of these, ADG was numerically increased ($P > 0.10$) in 10 comparisons (average of 2.9%) and numerically decreased ($P > 0.10$)

in 8 comparisons (average of 2.3%) compared to control pigs. Feed efficiency significantly increased ($P \leq 0.05$) in 10 comparisons (average of 9.0%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in G:F (19 comparisons). Of these, G:F was numerically increased ($P > 0.10$) in 12 comparisons (average of 1.8%) and numerically decreased ($P > 0.10$) in 5 comparisons (average of 3.3%) compared to control pigs. Overall, the results suggest that multi-enzymes have positive effects on ADG and G:F (69 and 76% of all the comparisons), and multi-enzymes significantly improved ($P \leq 0.05$) ADG and G:F in 34% of all the comparisons. Moreover, the combination of multiple enzymes provided greater improvement than adding any single type of enzyme (carbohydrase, protease, and phytase) alone, which suggests that different types of enzymes may have a synergetic effect. However, most comparisons showed little or negative effects in US-based research; therefore, the utilization of multi-enzymes in US-based diets should be evaluated further. There are not enough data to support whether different basal diets affected the response to multi-enzymes for ADG or G:F. Nevertheless, similar to the results with carbohydrases, multi-enzymes improved pig performance when diets were marginal in nutrient concentrations. In summary, there was a low chance of negative effects by feeding multi-enzymes and they can potentially improve growth performance (approximately 3% improvement for ADG and G:F).

7. *Carcass Characteristics - Multi-enzymes*

Back-fat significantly decreased ($P \leq 0.05$) in 1 comparison (10.2%) compared to control pigs (Table A.22). The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in BF (11 comparisons). Of these, BF was numerically increased ($P > 0.10$) in 6 comparisons (average of 10.4%) and numerically decreased ($P > 0.10$) in 5 comparisons (average of 3.8%) compared to control pigs. Percentage lean significantly increased ($P \leq 0.05$) in

1 comparison (4.4%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in percentage lean (8 comparisons). Of these, percentage lean was numerically increased ($P > 0.10$) in 6 comparisons (average of 0.6%) and numerically decreased ($P > 0.10$) in 2 comparisons (average of 0.9%) compared to control pigs. Loin muscle area/depth significantly increased ($P \leq 0.05$) in 1 comparison (11.3%) compared to control pigs. The greatest proportion of the comparisons found no evidence of difference ($P > 0.10$) in LMA/LD (7 comparisons). Of these, LMA/LD was numerically increased ($P > 0.10$) in 3 comparisons (average of 1.8%) and numerically decreased ($P > 0.10$) in 5 comparisons (average of 2.8%) compared to control pigs.

Conclusion

In conclusion, this literature review collected available research on finishing pig feed additives to provide a descriptive analysis of the effects on growth and carcass performance and provides a database that can be further analyzed with advanced statistical methods, such as meta-analysis, in the hope of better understanding the effect of feed additives to improve the efficiency of swine production.

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