Effects of Polyunsaturated Fatty Acids Supplementation on The Meat Quality of Pigs: A Meta-Analysis

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Research

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Abstract

Background: Polyunsaturated fatty acids (PUFAs) supplementation has been widely discussed as a strategy for improving meat quality in pig production but the effects are inconsistent. This meta-analysis was performed to comprehensively evaluate its effects on the meat quality including intramuscular fat (IMF) content, drip loss, meat color, pH 45min and pH 24h of pigs.

Methods: We searched the PubMed and Web of Science databases (articles published from Jan 1st, 2000, and Oct 16th, 2020) and compared PUFAs-supplemented diets with control diets. We identified 1670 studies, of which 14 (with data for 752 pigs) were included in our meta-analysis. We used a random-effects model and a fixed-effects model to calculate the weighted mean differences (WMDs) and 95% confidence intervals (CIs). We used sensitivity and subgroup analysis to ensure the pooled estimates are robust. The subgroup analysis was classified as treatment (conjugated linoleic acid (CLA) or linseed), concentration (high or low concentration) and initial stage (growing and finishing pigs).

Results: Our analysis found that PUFAs supplementation increased the IMF content (WMD= 0.467%, 95% CI: 0.312 to 0.621, *P*<0.001), decreased the meat color L* (WMD= -0.636, 95% CI: -1.225 to -0.047, *P*=0.034) and pH 24h (WMD= -0.021,95% CI: -0.032 to -0.009, *P*<0.001). CLA supplementation improved IMF content (WMD= 0.542%, 95% CI: 0.343 to 0.741, *P*<0.001) and reduced meat color b* (WMD= -0.194, 95% CI: -0.344 to -0.044, *P*=0.011). Linseed supplementation increased IMF content (WMD= 0.307%, 95% CI: 0.047 to 0.566, *P*=0.021), decreased meat color L*(WMD= -1.740, 95% CI: -3.267 to -0.213, *P*=0.026) and pH 24h (WMD= -0.034, 95% CI: -0.049 to -0.018, *P*<0.001). We discovered an increase on IMF content in both high and low concentration PUFAs supplementation (WMD= 0.461%, 95% CI: -0.344 to -0.044, P<0.001; WMD= 0.456%, 95% CI: 0.276 to 0.635, P<0.001). Besides, we also found the effects of PUFAs supplementation on meat color L* and pH 24h are concentration- and stage-dependent.

Conclusions: PUFAs supplementation can improve meat quality of pigs which mainly emerge in greatly increasing IMF content.

Background

There has been an increased interest in recent years in ways to produce high quality pork in pig production. This is because pork is one of the most produced and consumed meats in the world and is an important source of human protein and fatty acid, especially of saturated fatty acids, which is closely related to human health[1]. The main indexes to evaluate the pork quality include intramuscular fat content, drip loss, meat color, pH, juiciness, tenderness, flavor, fatty acid composition, and so on. Multiple factors can influence pork quality, such as nutrition, genetics, environment, management practices, and production systems[2]. Hence, it is of great significance to improve pork quality via seeking effective strategies.

Nutritional regulation is one of the safe and acceptable methods to improve meat quality of pigs. Previous studies have found that dietary fatty acid composition plays an important role in regulating the nutritional quality of pork not only in lean breeds pigs but also in Chinese indigenous breeds pigs[3, 4]. It is an acceptable and effective strategy for consumers to improve meat quality of pigs through added fatty acids supplementation in diet. Polyunsaturated fatty acids (PUFAs) are one of essential fatty acids, including n-3 PUFAs, n-6 PUFAs and n-9 PUFAs. PUFAs play an irreplaceable role in regulating fat deposition, muscle development and glycolipid metabolism[5–7]. In recent years, many studies have conducted the feeding trials on pigs to explore the effects of PUFAs on meat quality whereas the results are inconsistent. We discovered several factors such as different treatment supplementation (conjugated linoleic acid (CLA) or linseed), added concentration (high concentration or low concentration) and initial growth stage of pigs (growing or finishing pigs) led to the inconsistent results by further comparison.

The aim of our study was to reveal and identify the main effects or the effect orientation of PUFAs supplementation on meat quality of pigs by performing a meta-analysis. We also elucidated the potential influential factors based on the outcomes including intramuscular fat (IMF) content, drip loss, meat color, pH 45 min and pH 24 h. This is the first comprehensive and systematic meta-analysis focus on this topic and provide useful strategies for producing high quality pork in pig industry.

Methods

We conducted and reported the meta-analysis strictly followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement[8].

Search strategy

We collected the last 20 years studies published between Jan 1st, 2000, and Oct 16th, 2020, in the PubMed (https://www.thncbi.nlm.nih.gov/pubmed; accessed Oct 16th, 2020) and Web of Science (http://webofknowledge.com; accessed Oct 16th, 2020) databases. We applied no language restrictions. The complete search principles were as follows: 1) the term “pigs” was searched in the PubMed database beforehand and shown to be “swine”, “suidae”, “warthogs”, “wart hogs”, “hog, wart”, “hogs, wart”, “wart hog”, and “phacochoerus”; 2) similarly, the terms related to polyunsaturated fatty acids were extended to include “fatty acids, unsaturated”, “acids, unsaturated fatty”, “unsaturated fatty acids”, “acids, unsaturated fatty” and “fatty acids, polyunsaturated”; and 3) meat quality was equal to pork quality and meat

characteristic. The detailed search strategy and findings are shown in Table 1. We considered all potentially eligible studies instead of the primary outcome or language. We also did a manual search to obtain more studies. The complete search method was shown in Table 1.

Table 1
Search strategy

Search	Query	Items found
PubMed		
#1	Search: (((((((((Swine) or Suidae) or Pigs) or Warthogs) or Wart Hogs) or Hog, Wart) or Hogs, Wart) or Wart Hog) or Phacochoerus)); Filters: Publication date from 2000/01/01 to 2020/10/16	157,481
#2	Search: ((((((Fatty Acids, Unsaturated) or Acids, Unsaturated Fatty) or Unsaturated Fatty Acids) or Polyunsaturated Fatty Acids) or Acids, Polyunsaturated Fatty) or Fatty Acids, Polyunsaturated))	122,686
#3	Search: (((meat quality) or pork quality) or meat characteristic))	18,919
#1 AND #2 AND #3		274
Web of science		
#1	TS= (Swine or Suidae or Pigs or Warthogs or Wart Hogs or Hog, Wart or Hogs, Wart or Wart Hog or Phacochoerus)	411,441
#2	TS= (Fatty Acids, Unsaturated or Acids, Unsaturated Fatty or Unsaturated Fatty Acids or Polyunsaturated Fatty Acids or Acids, Polyunsaturated Fatty or Fatty Acids, Polyunsaturated)	102,584
#3	TS= (meat quality or pork quality or meat characteristic)	117,463
#1 AND #2 AND #3		1396

Selection criteria and procedure

We regarded studies as eligible for inclusion if they met the following criteria:1) studies reported the effects of PUFAs on meat quality (IMF, drip loss, meat color, pH 45 min and pH 24 h); 2) PUFAs, PUFA-rich compounds, PUFA supplements or PUFA extracts were added to the feed throughout the experimental period; 3) the growth stage of pigs was growing or finishing; and 4) the concentration of PUFA supplements was reported. The exclusion criteria were as follows:1) studies lacked a control group; 2) studies are proceedings papers; 3) studies lacked full-text online resource; 4) studies used mixed additives; and 5) studies investigated piglets. Based on these criteria, we screened eligible studies for subsequent meta-analysis (Fig. 1a).

The following information were extracted from each selected study: author information (first author, year, country); genetic background; treatment; experimental duration; concentration; sum number of pigs included in the control and treatment groups; sex; growth stage (growing, finishing or growing-finishing), and outcomes of meat quality (IMF, drip loss, meat color, pH45min and pH24h). One study might have more than one record due to the duration of the pigs and concentration of supplemental substance.

The study selection procedure was as follow: 1) Two investigators (L.Wang and Y. Huang) independently screened the titles and abstracts of the articles according to the inclusion criteria; 2) disagreements during independent selection were solved through consultation with a third author (T. Shan); and 3) after the included studies were verified and confirmed, one investigator (L.Wang) extracted the data and information from each study and the other investigator (Y. Huang) checked. The summarized information of included studies was showed in Table 2.

Table 2

Characteristics of included studies [a]

Study	Year	Country	Genetic background	Treatment	Duration	Concentration	N [b]	Sex	Growth stage	Outcomes [c]
O'Quinn et al.	2000	American	PIC L326 or 327 boars × C22 sows	CLA 60	37.6 kg to 106.4 kg	50%	24	Barrows	Growing-finishing pigs	drip loss, meat color
Wiegand et al.	2001	American	NA	Conjugated linoleic acid	40 kg to 106 kg	0.75%	20	Barrows	Growing-finishing pigs	IMF, meat color
Joo et al.	2002	Korea	Landrace × Large White × Duroc	Conjugated linoleic acid	4 weeks	1%, 2.5%, 5%	20	Gilts	Finishing pigs	IMF, drip loss, meat color, pH 24 h
Tischendorf et al.	2002	Germany	Pietrain × (Landrace × Large White)	Conjugated linoleic acid	8 weeks	2%	40	20 female and 20 male-castrated	Growing-finishing pigs	IMF, drip loss, meat color, pH 45 min, pH 24 h
Corino et al.	2003	Italy	Large White	Conjugated linoleic acid	97 kg to 172 kg	0.25%, 0.5%	36	18 barrows and 18 gilts	Finishing pigs	meat color, pH 45 min, pH 24 h
Dugan et al.	2003	Canada	NA	Conjugated linoleic acid	35 kg to 115 kg	0.25%, 0.5%	108	NA	Growing-finishing pigs	IMF, drip loss, meat color, pH 24 h
Sun et al.	2004	China	Duroc × Landrace × Large White	Conjugated linoleic acid	3, 6 weeks	2%, 4%	54	Crossbred barrows	Finishing pigs	IMF, drip loss
Luo et al.	2009	China	Landrace × NewDamLine	Linseed	30, 60, 90 days	10%	24	Barrows	Growing-finishing pigs	IMF, drip loss, pH 45 min
Dannenberger et al.	2012	Germany	Landrace	High, reduced protein diet with linseed oil	60 ~ 100 kg to 120 kg	4.5%	24	Male-castrated	Finishing pigs	IMF, drip loss, meat color, pH 45 min, pH 24 h
Huang et al.	2014	China	Rongchang pigs	Conjugated linoleic acid	30 kg to 60 kg, 60 kg to 90 kg	0.5%, 1%, 1.5%, 2%	160	NA	Growing-finishing pigs	IMF, meat color, pH 45 min, pH 24 h
Deng et al.	2019	China	NA	Flaxseed	72 days	5%, 10%	72	NA	Growing-finishing pigs	Ether extract, drip loss, meat color, pH 45 min, pH 24 h
Nevrkla et al.	2019	Czech Republic	(Large White × Landrace) × (Duroc × Pietrain)	Linseed	57 days	7%	40	Gilts	Finishing pigs	IMF, drip loss, pH 45 min, pH 24 h
Trombetta et al.	2019	Brazil	50% Large White × 50% Landrace	Linseed oil	90 days	3%	22	10 castrated males and 12 females	Finishing pigs	IMF, drip loss, meat color, pH 24 h
Chang Hyun et al.	2020	Korea	Landrace × Yorkshire × Duroc	Linseed (n-6: n-3 PUFA ratio)	NA	1.5% (4:1), 3% (2:1)	108	NA	Finishing pigs	drip loss, meat color, pH 45 min, pH 24 h

[a] NA, not available

[b] Number of pigs included in studies

[c] IMF, intramuscular fat; pH 45 min, pH value measured at 45 min postmortem; pH 24 h, pH value measured at 24-hour postmortem

Study quality assessment

Two investigators (L.Wang and Y.Huang) independently assessed the quality assessment of included studies by using two methods: Cochrane handbook for systematic review of interventions[9] and the Study Quality Assessment on Nonruminants (SQANR)[10], which is a new assessment method for feeding trials. Articles were judged as high risk, low risk or unclear in the following aspects: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting and other bias in which the assessment of other bias according to the final score of SQANR (Fig. 1b and Table S2).

Within-group standard deviation estimate

We obtained the within-group standard deviation (SD) by the following three approaches: 1) used the within-group standard error (SE) to calculate; 2) contacted the authors via emails if the study has neither the within-group SD or SE; and 3) used pooled SD as within-group SD which was calculated from standard error of mean (SEM), and pooled SD is equal to SEM multiplied by the square root of the number of groups[11].

Statistical analysis

The statistical analysis was performed with Stata 15.1 (Stata Corp., USA).

Meta-analysis

For continuous outcomes, as data the units of measure are the same and the mean varies little, we used a random-effects model to calculate the overall effect as weighted mean difference (WMD) and 95% CI between the treatment and control groups. If the 95% CI contained a zero value, there was no difference. We also used Cochran's Q test (significance level of $P \leq 0.1$) and the I^2 statistic to assess the degree of statistical heterogeneity among studies, with a value of < 25%, 25–50%, 51%-75% and > 75% considered as no, low, moderate, and high level of heterogeneity, respectively[12]. Specially, we changed to fixed-effects model if the statistics of study has homogeneity, namely $I^2 < 50\%$.

Regression analysis

We performed a meta-regression analysis to explore the potential sources of heterogeneity and define the effects of covariates on outcomes (IMF, drip loss, meat color, pH 45 min and pH 24 h)[13]. The covariates were as follows: treatment (conjugated linoleic acid (CLA) or linseed), concentration (high concentration (> 2%) or low concentration (≤ 2%)) and initial growth stage (growing pigs or finishing pigs). The regression analysis was applied only to groups with 10 or more records to avoid a false positive result.

Subgroup analysis and sensitivity analysis

We conducted a subgroup analysis if the study was regarded as a moderate or high heterogeneity ($I^2 > 50\%$). We classified the subgroups in three groups: CLA group or linseed group, high concentration group or low concentration group and growing pigs group or finishing pigs group. If the heterogeneity was significant ($P < 0.05$), we also performed a sensitivity analysis to identify which study (or studies) contributing to the heterogeneity using the leave-one-out method. Heterogeneity and pooled analyses were recalculated after a single study was removed from the outcome at a time. We included data which the source of heterogeneity was identified and exclusion these data did not influence the pooled estimates.

Publication bias

The potential publication bias was investigated by funnel plot asymmetry (Fig.S1), Begg's and Egger's weighted regression test, for which the significance level was defined at $P < 0.05$[14]. We used Egger's test as a reference if funnel plot asymmetry, Begg's and Egger's tests disagreed. In addition, the trim-and-fill test was used to estimate the effect of publication bias on the interpretation of the results[15].

Results

We identified 1670 studies, of which 14 (with data for 752 pigs) were included in our meta-analysis (Fig. 1a)[16–29]. The 14 studies were all published between 2000 and 2020, there was no repetition between studies (Table 1). These studies investigated the effects of PUFAs supplementation on meat quality (IMF, drip loss, meat color, pH 45 min and pH 24 h), among the selected studies there are 8 added conjugated linoleic acid and 6 added linseed or linseed oil, 7 studies (14 records) began at grower phase and 7 studies (17 records) began at finisher phase. The study quality assessment was shown in Fig. 1b. We defined the risk of detection bias as unclear because the blinding of outcome assessment was not reported in the included studies. Other bias was assessed based on the final score of SQANR (TableS2), there are 9 studies have unclear risk and 5 have high risk. According to funnel plot (Fig.S1), Begg's and Egger's tests, the publication bias was not significant ($P > 0.05$) in the current meta-analysis (Table 3), so the trim-and-fill test was not necessary to perform.

Table 3
The summary of meta-analysis and publication bias analysis of the included studies

Outcome [a]	N [b]	WMD (95% CI) [c]	*P*	I^2	$P_{heterogeneity}$	Begg's Test	Egger's test
IMF (%)	26	0.467 (0.312 to 0.621)	< 0.001	87.0%	< 0.001	0.005	0.085
Drip loss (%)	24	-0.191 (-0.458 to 0.075)	0.159	63.4%	< 0.001	0.861	0.439
L*	25	-0.636 (-1.225 to -0.047)	0.034	65.5%	< 0.001	0.110	0.509
a*	25	0.081 (-0.244 to 0.406)	0.625	67.5%	< 0.001	1.000	0.614
b*	25	-0.123 (-0.268 to 0.022)	0.095	53.4%	0.001	0.158	0.136
pH 45 min	24	0.038 (-0.042 to 0.117)	0.351	71.9%	< 0.001	0.053	0.114
pH 24 h	24	-0.021 (-0.032 to -0.009)	< 0.001	11.6%	0.300	0.516	0.229

[a] L*, lightness, a*, redness, b*, yellowness

[b] N, number of comparisons;

[c] WMD, weighted mean difference; CI, confidence interval.

Effects of PUFAs supplementation on the meat quality of pigs

As shown in Table 3, we presented the effects of PUFAs supplementation on the meat quality of pigs. PUFAs supplementation increased the content of IMF by 0.467% (95% confidence interval (CI): 0.312 to 0.621, $P < 0.001$) with high heterogeneity ($I^2 = 87.0\%$, $P_{heterogeneity} < 0.001$), decreased the meat color L* by 0.636 (95% CI: -1.225 to -0.047, $P = 0.034$) with moderate heterogeneity ($I^2 = 65.5\%$, $P_{heterogeneity} < 0.001$) and decreased the pH 24 h by 0.021 (95% CI: -0.032 to -0.009, $P < 0.001$) with no heterogeneity ($I^2 = 11.6\%$, $P_{heterogeneity} = 0.300$). However, PUFAs supplementation had no effect on the drip loss (WMD= -0.191, 95% CI: -0.458 to 0.075, $P = 0.159$) with moderate heterogeneity ($I^2 = 63.4\%$, $P_{heterogeneity} < 0.001$), meat color a* (WMD = 0.081, 95% CI: -0.244 to 0.406, $P = 0.625$) with moderate heterogeneity ($I^2 = 67.5\%$, $P_{heterogeneity} < 0.001$), meat color b* (WMD= -0.123, 95% CI: -0.268 to 0.022, $P = 0.095$) with moderate heterogeneity ($I^2 = 53.4\%$, $P_{heterogeneity} = 0.001$) and pH 45 min (WMD = 0.038, 95% CI: -0.042 to 0.117, $P = 0.351$) with moderate heterogeneity ($I^2 = 71.9\%$, $P_{heterogeneity} < 0.001$).

Regression analysis

To explore the potential sources of heterogeneity and define the effects of covariates on meat quality, we performed a meta-regression analysis (Table 4). We found treatment, concentration and initial growth stage might played an important role in affecting the meat quality especially IMF content, because $P_{regression}$ was 0.009, 0.010 and 0.002, respectively. Therefore, we performed subgroup analysis of treatment, concentration and initial growth stage in the subsequent research.

Table 4
Regression and subgroup analysis of studies included in the meta-analysis

Outcome	Subgroup		$P_{regression}$ [a]	WMD (95% CI)	P	I^2	$P_{heterogeneity}$
IMF (%)	Treatment	CLA	0.009	0.542 (0.343 to 0.741)	< 0.001	86.4%	< 0.001
		Linseed		0.307 (0.047 to 0.566)	0.021	86.6%	< 0.001
	Concentration	High concentration	0.010	0.461 (0.208 to 0.715)	< 0.001	92.2%	< 0.001
		Low concentration		0.456 (0.276 to 0.635)	< 0.001	72.0%	< 0.001
	Initial growth stage	Growing pigs	0.002	0.563 (0.395 to 0.731)	< 0.001	75.7%	< 0.001
		Finishing pigs		0.254 (-0.061 to 0.569)	0.114	93.6%	< 0.001
Drip loss (%)	Treatment	CLA	0.811	-0.147 (-0.314 to 0.021)	0.086	0.0%	0.857
		Linseed		-0.299(-0.959 to 0.361)	0.374	81.9%	< 0.001
	Concentration	High concentration	0.878	-0.268(-0.775 to 0.240))	0.301	74.9%	< 0.001
		Low concentration		-0.128 (-0.307 to 0.050)	0.159	0.0%	0.878
	Initial growth stage	Growing pigs	0.849	-0.135 (-0.301 to 0.031)	0.111	0.0%	0.777
		Finishing pigs		-0.258 (-0.955 to 0.440)	0.469	81.6%	< 0.001
L*	Treatment	CLA	0.212	-0.155 (-0.590 to 0.280)	0.485	14.0%	0.287
		Linseed		-1.740 (-3.267 to -0.213)	0.026	81.9%	< 0.001
	Concentration	High concentration	0.932	-1.366 (-2.717 to -0.015)	0.047	78.9%	< 0.001
		Low concentration		-0.172 (-0.627 to 0.283)	0.459	17.4%	0.254
	Initial growth stage	Growing pigs	0.253	-0.091 (-0.652 to 0.470)	0.750	34.5%	0.092
		Finishing pigs		-1.331 (-2.354 to -0.308)	0.011	72.5%	< 0.001
a*	Treatment	CLA	0.401	0.137 (-0.265 to 0.538)	0.504	73.3%	< 0.001
		Linseed		-0.066 (-0.578 to 0.446)	0.800	36.8%	0.148
	Concentration	High concentration	0.165	0.146 (-0.364 to 0.656)	0.574	54.7%	0.024
		Low concentration		0.053 (-0.370 to 0.476)	0.806	73.0%	< 0.001
	Initial growth stage	Growing pigs	0.090	0.227 (-0.141 to 0.595)	0.226	61.7%	0.001
		Finishing pigs		-0.255 (-0.900 to 0.391)	0.439	75.8%	< 0.001
b*	Treatment	CLA	0.134	-0.194 (-0.344 to -0.044)	0.011	52.7%	0.005
		Linseed		0.184 (-0.140 to 0.508)	0.265	26.7%	0.225
	Concentration	High concentration	0.878	0.032 (-0.209 to 0.273)	0.794	17.1%	0.290
		Low concentration		-0.180 (-0.351 to -0.009)	0.039	60.3%	0.001
	Initial growth stage	Growing pigs	0.652	-0.163 (-0.295 to -0.030)	0.016	32.0%	0.112
		Finishing pigs		-0.104 (-0.475 to 0.267)	0.583	70.0%	< 0.001
pH 45 min	Treatment	CLA	0.769	0.019 (-0.095 to 0.132)	0.749	64.1%	0.003
		Linseed		0.056 (-0.059 to 0.172)	0.337	77.7%	0.002
	Concentration	High concentration	0.771	0.058 (-0.064 to 0.179)	0.352	79.9%	< 0.001
		Low concentration		0.021 (-0.086 to 0.128)	0.704	60.6%	0.003
	Initial growth stage	Growing pigs	0.169	-0.003 (-0.078 to 0.072)	0.940	31.6%	0.123
		Finishing pigs		0.106 (-0.054 to 0.266)	0.195	87.5%	< 0.001
pH 24 h	Treatment	CLA	0.738	-0.006 (-0.023 to 0.11)	0.486	0.0%	0.568
		Linseed		-0.034 (-0.049 to -0.018)	< 0.001	1.2%	0.420

Outcome	Subgroup		$P_{regression}$ [a]	WMD (95% CI)	P	I^2	$P_{heterogeneity}$
	Concentration	High concentration	0.669	-0.033 (-0.049 to -0.018)	< 0.001	0.0%	0.526
		Low concentration		-0.006 (-0.023 to 0.011)	0.479	0.0%	0.486
	Initial growth stage	Growing pigs	0.093	-0.002 (-0.019 to 0.015)	0.813	0.0%	0.783
		Finishing pigs		-0.035 (-0.051 to -0.020)	< 0.001	0.7%	0.434

[a] $P_{regression}$, P value of regression, significance level $P_{regression} < 0.05$

Effects of CLA and linseed supplementation on the meat quality of pigs

To explain the effects of CLA and linseed supplementation on the meat quality of pigs, we performed a subgroup analysis of different treatment (CLA and linseed (linseed or linseed oil)). As shown in Fig. 2 and Table 4, both CLA and linseed supplementation increased IMF content by 0.542% (95% CI: 0.343 to 0.741, $P < 0.001$) with high heterogeneity ($I^2 = 86.4\%$, $P_{heterogeneity}<0.001$) and 0.307% (95% CI: 0.047 to 0.566, $P = 0.021$) with high heterogeneity ($I^2 = 86.6\%$, $P_{heterogeneity}<0.001$). CLA supplementation can decrease meat color b* by 0.194 (95% CI: -0.344 to -0.044, $P = 0.011$) with moderate heterogeneity ($I^2 = 52.7\%$, $P_{heterogeneity} = 0.005$). However, there are no effects on drip loss, meat color L*, meat color b*, pH 45 min and pH 24 h ($P > 0.05$) (Table 4). Besides, linseed and linseed oil decreased meat color L* (WMD= -1.740, 95% CI: -3.267 to -0.213, $P = 0.026$) with high heterogeneity ($I^2 = 81.9\%$, $P_{heterogeneity} <0.001$) and pH 24 h (WMD= -0.034, 95% CI: -0.049 to -0.018, $P < 0.001$) with no heterogeneity ($I^2 = 1.2\%$, $P_{heterogeneity} = 0.420$). We found nonsignificant differences in other meat quality indexes ($P > 0.05$) (Table 4).

Effects of different PUFAs supplementation concentration on the meat quality of pigs

To explore the effects of different PUFAs supplementation concentration on the meat quality of pigs, we performed a subgroup analysis of different concentration (high concentration (> 2%) and low concentration (≤ 2%)). As presented in Fig. 3 and Table 4, not only high concentration but also low concentration improved IMF content by 0.461% (95% CI: 0.208 to 0.715, $P < 0.001$) with high heterogeneity ($I^2 = 92.2\%$, $P_{heterogeneity}<0.001$) and 0.456% (95% CI: 0.276 to 0.635, $P < 0.001$) with moderate heterogeneity ($I^2 = 72.0\%$, $P_{heterogeneity}<0.001$). High PUFAs supplementation concentration decreased meat color L* (WMD= -1.366, 95% CI: -2.717 to -0.015, $P = 0.047$) with high heterogeneity ($I^2 = 78.9\%$, $P_{heterogeneity}<0.001$) and pH 24 h (WMD= -0.033, 95% CI: -0.049 to -0.018, $P < 0.001$) with no heterogeneity ($I^2 = 0.0\%$, $P_{heterogeneity} = 0.526$). Additionally, we found low concentration reduced meat color b* by 0.180 (95% CI: -0.351 to -0.009, $P = 0.039$) with moderate heterogeneity ($I^2 = 60.3\%$, $P_{heterogeneity} = 0.001$). There are no significant differences on other indexes (drip loss, meat color a* and pH 45 min, $P > 0.05$) (Table 4).

Effects of PUFAs supplementation on the meat quality of growing and finishing pigs

As shown in Fig. 4 and Table 4, for growing pigs, PUFAs supplementation increased IMF content by 0.563% (95% CI: 0.395 to 0.731, $P < 0.001$) with high heterogeneity ($I^2 = 75.7\%$, $P_{heterogeneity}<0.001$) whereas decreased meat color b* by 0. 163 (95% CI: -0.295 to -0.030, $P = 0.016$) with low heterogeneity ($I^2 = 32.0\%$, $P_{heterogeneity} = 0.112$) and pH 24 h by 0.035 (95% CI: -0.051 to -0.020, $P < 0.001$) with no heterogeneity ($I^2 = 0.7\%$, $P_{heterogeneity} = 0.434$). Moreover, PUFAs supplementation reduced meat color L* by 1.331 (95% CI: -2.354 to -0.308, $P = 0.011$) with moderate heterogeneity ($I^2 = 72.5\%$, $P_{heterogeneity}<0.001$) in finishing pigs. We found PUFAs supplementation had no influence on drip loss, meat color a* and pH 45 min in both growing pigs and finishing pigs ($P > 0.05$) (Table 4).

Discussion

Our meta-analysis results show that PUFAs supplementation can significantly increase IMF content but decrease meat color L* and pH 24 h in pigs (Table 3). Specially, whatever CLA or linseed and high concentration or low concentration PUFAs supplementation can improve IMF content (Fig. 2a and Fig. 3a). However, PUFAs supplementation has no effect on IMF content in finishing pigs (Fig. 4). Furthermore, CLA supplementation reduced meat color b* and linseed supplementation decreased meat color L* and pH 24 h (Fig. 2). We also found the effects of PUFAs supplementation on meat color L* and pH 24 h are concentration- and stage- dependent (Fig. 3 and Fig. 4). Overall, these data support that PUFAs supplementation are benefit for improving meat quality in pigs.

In pig production, meat quality has been declining in recent years due to the blindly pursuit of production efficiency and increase of backfat thickness. It has been reported that the content of IMF is positively related to pork quality including tenderness, flavor, and juiciness[30]. IMF is mainly distributed in the epimysium, perimysium and endomysium of skeletal muscle which the main components are phosphoric acid and triglyceride. Previous studies found that IMF content is related to breed, sex, diet and weight at slaughter in pigs[31–33]. In our meta-analysis, we observed that dietary PUFAs supplementation can increase IMF content, not only CLA but also linseed supplementation significantly improved IMF content and CLA supplementation are more effective (Fig. 2a). Besides, we found the benefit of PUFAs supplementation on IMF content are not

dependent on concentration (Fig. 3a). Hence, PUFAs supplementation can be a nutritional measure to regulate meat quality. However, only growing pigs had an increased IMF content after fed PUFAs supplementation, finishing pigs had an insignificant effect (Fig. 4a). It might because the nutrition requirements of different growth stage pigs are different. Meat color and pH are one of the most important factors that affect sensory quality of pork. Specially, low pH value (below 5.8) is often associated with pale meat color, resulting in pale, soft and exudative (PSE) pork. In contrast, high meat pH (above 6.0) often causes dark, firm and dry (DFD) pork. The alteration of meat color and pH results from the different post-mortem processes including muscle metabolism (glycolysis) and conversion rates of glycogen into lactic acid, which are affected by environmental factors, such as nutrition, breeding conditions, transport conditions, stress, weather conditions, and the methods of slaughter[34]. However, current studies on the effects of PUFAs supplementation on meat color and pH 24 h are controversial. In our analysis, dietary PUFAs supplementation significantly decreased L* and pH 24 h but drip loss, a*, b* and pH 45 min were not influenced (Table 3). CLA is a group of positional and geometric isomers of linoleic acid with a conjugated double bond which is generally found in ruminant animals and dairy products and has many physiological functions including anti-obesity, anti-diabetic, anti-cancer and anti-hypertension[35]. Linseed is the ripe seed of flax which is rich in n-3 PUFAs and has anti-obesity, anti-inflammatory, anti-cancer and regulating glucose and lipid metabolism effects[36]. Even though CLA and linseed are all PUFAs, they had different effects on L*, b* and pH 24 h (Fig. 2), it might result from different fatty acids composition. We also discovered that the effects of PUFAs supplementation on L*, b* and pH 24 h are dependent on concentration and growth stage (Fig. 3 and Fig. 4). In addition, we found neither pH 24 h values above 6.0 nor pH 45 min below 5.8 in any studies. Hence, PUFAs supplementation might provide a useful strategy to improve meat quality.

As shown in Table 4, the significant heterogeneity in the drip loss and L*of pigs was primarily driven by the linseed, high-concentration and finishing pigs subgroup. Differently, the CLA, low-concentration and finishing pigs subgroup are sources of b* heterogeneity. Linseed and growing pigs subgroup are the source of a* and pH 45 min heterogeneity, respectively. Because we did not find the source of IMF heterogeneity according to subgroup analysis, we performed a sensitivity analysis through using the leave-one-out method on IMF. However, the significant heterogeneity had no change after deleted each included study, thus we think the meta-analysis results are robust and the heterogeneity did not influence the significance of pooled estimates. Besides, we used a fixed-effects model to analyze pH 24 h due to the homogeneity ($I^2 < 50\%$).

A limitation of this meta-analysis is that the effects of PUFAs supplementation duration on meat quality of pigs and whether PUFAs supplementation could affect different breeds and sex of pigs are unknown as a result of the incomplete data and we think further studies should focus on these questions. Furthermore, as SD values are important for meta-analysis and they affect many estimates, including the weight of an individual study, the 95% CIs and heterogeneity, so the lack of within-group SD might influence the results of meta-analysis. We used pooled SD as within-group SD and its might be impacted by the number of groups and SEM. To verify our finding are reliable, we checked the consistency between 95% CI of pooled estimate and the significance and tendency of included studies. Hence, our results are valid and this method is appropriate for analyzing nonruminant studies which lack of within-group SD. Besides, there is another method can be used for estimating within-group SD which is suitable for studies that reported the median, range, and the size of a sample[37]. In a word, different approaches can be adopted to estimate within-group SD accordingly ensure the results of meta-analysis are reliable and robust.

Conclusions

Our results indicate that PUFAs supplementation increases IMF content, decreases meat color L* and pH 24 h but has no effect on drip loss, meat color a*, b* and pH 45 min in pigs. Specially, PUFAs supplementation has positive effects on IMF content in finishing pigs but not in growing pigs. CLA supplementation improves IMF content and reduces meat color b* whereas linseed supplementation leads to an increase in IMF content and a reduction in meat color L* and pH 24 h. Additionally, PUFAs supplementation has concentration- and stage- dependent effects on meat color L* and pH 24 h. Our systemic and comprehensive analysis suggest that PUFAs supplementation has beneficial influences on improving meat quality of pigs which mainly emerge in increasing IMF content. This may become an effective method for producing high quality pork in pig industry but the optimal PUFAs supplementation concentration needs to be further studied.

Abbreviations

CI, confidence interval; CLA, conjugated linoleic acid; DFD, dark, firm and dry; IMF, intramuscular fat; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; PSE, pale, soft and exudative; PUFAs, polyunsaturated fatty acids; SD, standard deviation; SE, standard error; SEM, standard error of mean; SQANR, Study Quality Assessment on Nonruminants; WMD, weighted mean difference.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

Data can be available from the authors upon reasonable request.

Competing interests

The authors declare no conflict of interest.

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Authors' contributions

LW and YH participated in study quality assessment and study criteria selection. LW extracted data, conducted statistics analysis and wrote the final version of the manuscript. YH checked the data and assisted interpretation and revising the article. TS oversaw the development of the study and resolved conflicts in the meta-analysis. All authors have read and approved the final manuscript.

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Figures

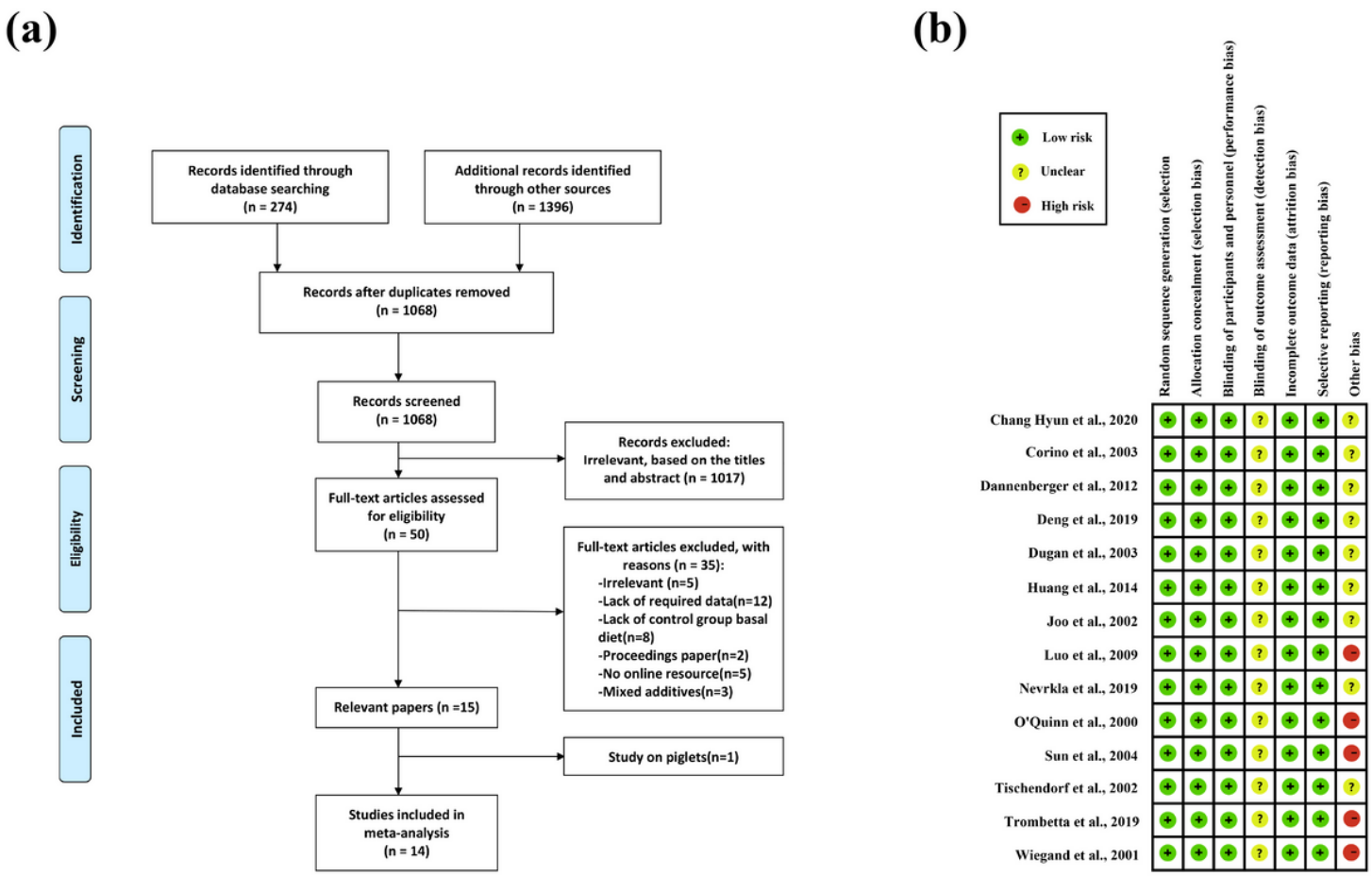

Figure 1

Study selection process and quality assessment. a Flowchart for study selection process. b Study quality assessment

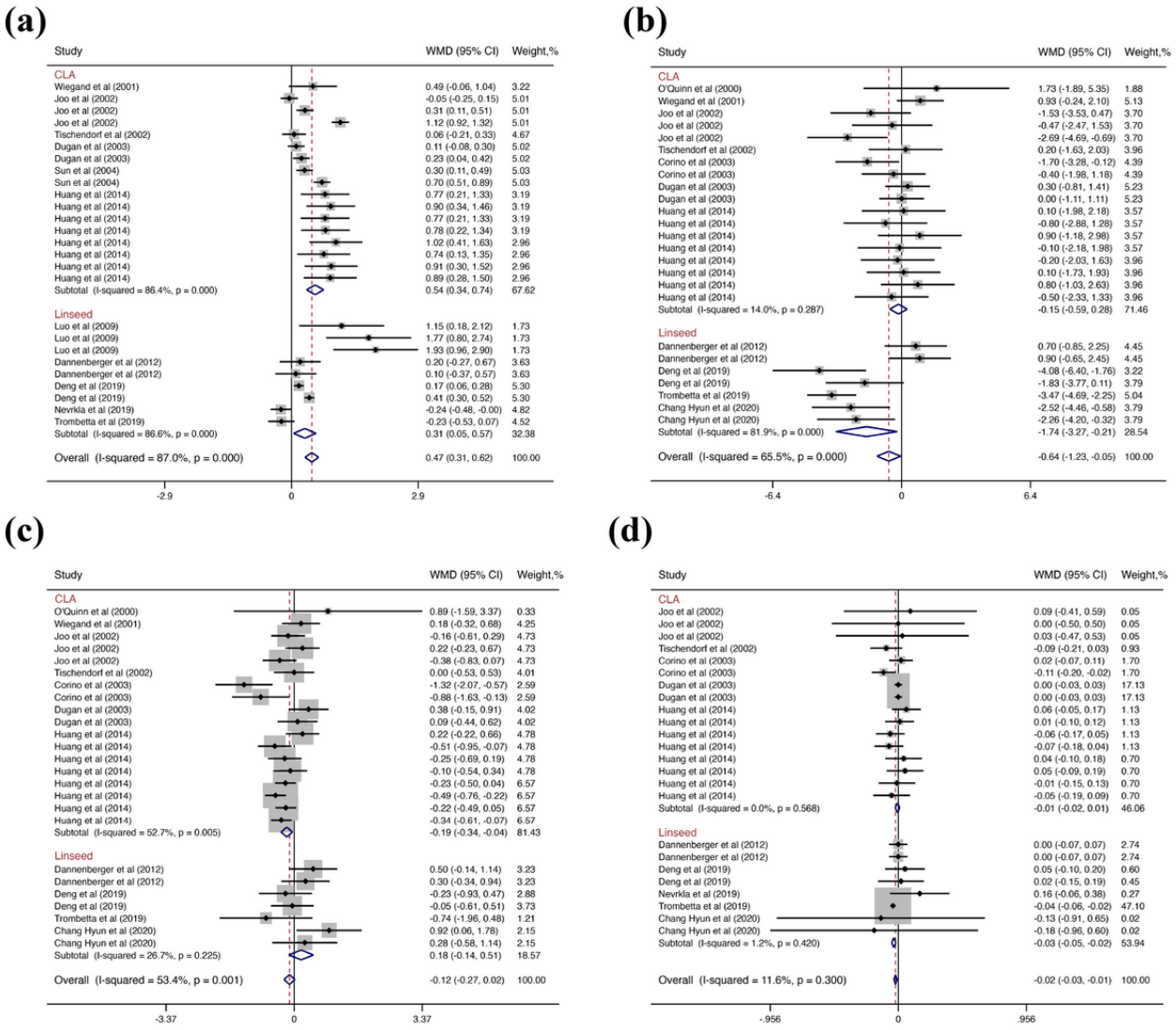

Figure 2

Forest plot of the effects of CLA or linseed on the meat quality of pigs. a IMF. b meat color L*. c meat color b*. d pH 24h. WMD, weighted mean difference; CI, confidence interval; CLA, conjugated linoleic acid. The small solid diamond represents the point estimate for each individual trial, and the horizontal line extending from each solid diamond represents the upper and lower limits of the 95% CI. The size of the shaded square indicates the relative weight of the trial in the meta-analysis. The hollow diamond represents the WMD and 95% CI of the trials, no intersection of the diamond and the solid black line in the middle indicates significant difference (P<0.05), vice versa.

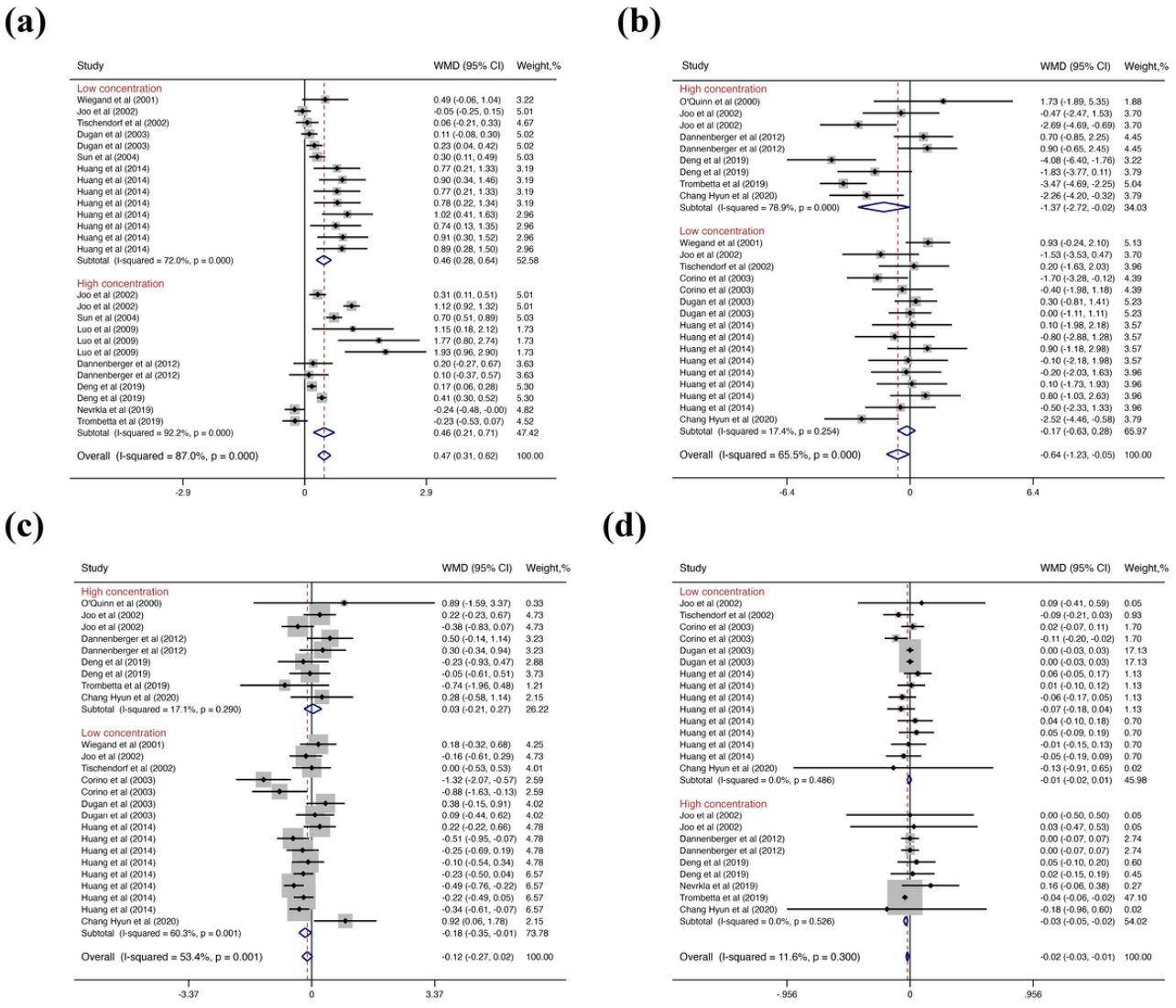

Figure 3

Forest plot of the differences in the meat quality of pigs fed high/low PUFA supplementation concentration. a IMF. b meat color L*. c meat color b*. d pH 24h. WMD, weighted mean difference; CI, confidence interval; CLA, conjugated linoleic acid. The small solid diamond represents the point estimate for each individual trial, and the horizontal line extending from each solid diamond represents the upper and lower limits of the 95% CI. The size of the shaded square indicates the relative weight of the trial in the meta-analysis. The hollow diamond represents the WMD and 95% CI of the trials, no intersection of the diamond and the solid black line in the middle indicates significant difference (P<0.05), vice versa.

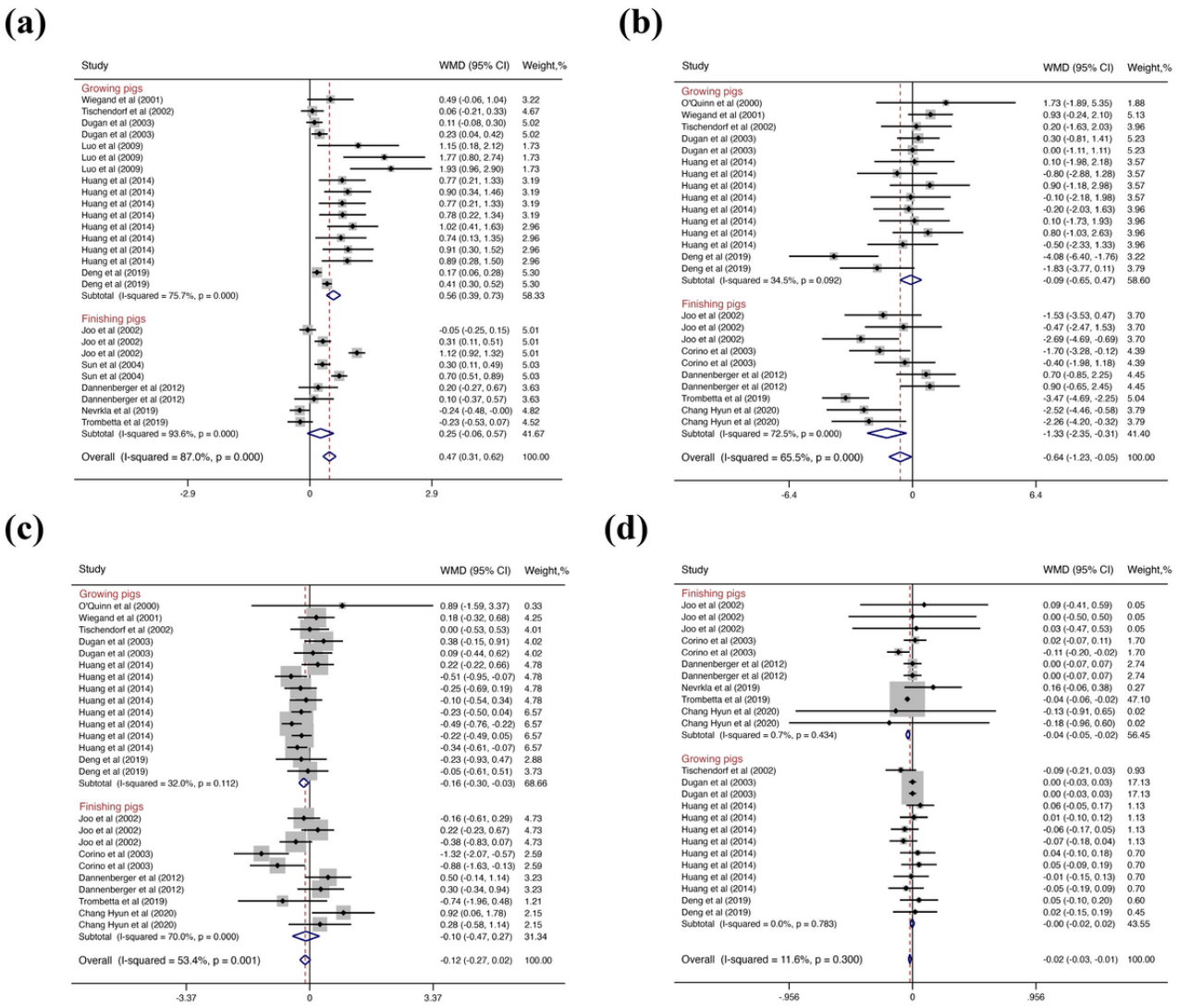

Figure 4

Forest plot of the effects of PUFA supplementation on the meat quality of growing and finishing pigs. a IMF. b meat color L*. c meat color b*. d pH 24h. WMD, weighted mean difference; CI, confidence interval; CLA, conjugated linoleic acid. The small solid diamond represents the point estimate for each individual trial, and the horizontal line extending from each solid diamond represents the upper and lower limits of the 95% CI. The size of the shaded square indicates the relative weight of the trial in the meta-analysis. The hollow diamond represents the WMD and 95% CI of the trials, no intersection of the diamond and the solid black line in the middle indicates significant difference (P<0.05), vice versa.

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