Effects of increasing dietary fat inclusion from different sources on growth performance, carcass and meat traits, and pork nutritional profile quality

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Research

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Abstract

Background

There has been an increased interest in nutritional strategies to manipulate the fatty acid profile of pigs. Dietary regimens involving the use of oils that are high in monosaturated fatty acid (MUFA), primarily oleic acid (OA), such as canola oil (CO), as well as in omega (n)-3 polyunsaturated fatty acid (PUFA), which are found in fish oil (FO), have been investigated aiming healthier fatty acid profile cuts, with a higher ratio of n-3 to n-6 fatty acids. Therefore, the effects of including 3% soybean oil (SO), CO, or FO in growing-finishing pig diets vs. feeding a standard commercial diet with 1.5% SO (control) on growth performance, carcass traits, meat quality, consumer acceptability, and intramuscular fatty acid composition of the *longissimus lumborum* (LL) muscle were evaluated.

Results

Dietary treatments had no effect on overall growth performance and pig carcasses. Although loins from pigs fed diets containing either 3% SO or CO showed a reduction ($P = 0.05$) in Warner-Bratzler shear force, only the addition of 3% SO to pig diets resulted in loin chops that were rated higher ($P < 0.001$) for consumer overall liking. Adding either 3% SO or CO increased ($P < 0.01$) the percentages of OA and total MUFA in the LL intramuscular fat compared to control- or FO-fed pigs. However, intramuscular fat from 3% SO- or CO-fed pigs had the lowest ($P < 0.01$) proportion of total n-3 PUFA than control- or FO-fed pigs. Including 3% fat, regardless of source, reduced ($P < 0.01$) total PUFA, total n-6 PUFA, and PUFA:saturated fatty acid (SFA) ratio than control-fed pigs. Dietary FO inclusion decreased ($P < 0.01$) n-6:n-3 PUFA ratio, but also increased total SFA ($P < 0.01$) and atherogenic index ($P = 0.02$) in the LL intramuscular fat.

Conclusions

Although adding 3% CO or FO to pig diets provided slight nutritional benefits to consumers in terms of MUFA and long chain n-3 PUFA contents, respectively, formulating growing-finishing diets with 1.5% SO was adequate enough in terms of LL intramuscular fatty acids composition for high quality meat destined to human consumption.

Background

Nutritional interventions play a major role in efficiently producing lean, quality pork for processing and storage, including retail display. Apart from being recognized as excellent energy sources, fats comprise a practical dietary strategy for improving pig productivity [1]. Fat-rich diets have been implemented for growing-finishing pigs to decrease voluntary feed intake and improve feed efficiency [2, 3], as well as to alleviate the energy loss as heat increment, especially in heat stress conditions [4]. Additionally, fats are sources of fat-soluble vitamins, essential fatty acids, and may act as signaling molecules [5]. However, feeding supplemental fat to pigs may be limited by the cost effectiveness in least-cost formulation [6].

Collectively, all animal products provide 56% of the total fat, 74% of the saturated fatty acids (SFA), 70% of the protein, and 100% of the cholesterol consumed [7]. Dietary guidelines for humans in the last years have focused on limiting the intake of SFA-rich foods, including red meat, and replacing dietary SFA with monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) in view of the increasing evidences linking Western-style diets with metabolic diseases [8]. However, a systematic review demonstrated that diets restricted in red meat may have little or no effect on major cardiometabolic diseases and cancer mortality [9]. More recently, dietary guideline recommendations from the Nutritional Recommendations (NutriRECS) Consortium, which uses GRADE (Grading of Recommendations, Assessment, Development, and Evaluations) method, reported uncertainty association between red meat consumption and potential adverse health outcomes [10]. Even though lean pork is relatively rich in unsaturated fatty acids, especially MUFA, there may still be some health benefits in adjusting its fatty acid profile [11].

Considering that fatty acid deposition in pigs mostly reflects their dietary fatty acid profile [1], efforts to enrich pork meat with omega (n)-6 PUFA, mainly linoleic acid (C18:2 n-6) typically present in soybean oil (SO), have been extensively made in the last decades. Excessive n-6 PUFA content may lead to the prevalence of atherosclerosis, obesity, diabetes, and cancer [12]. Thus, there is an increased interest in the dietary regimens involving the use of oils that are high in MUFA, primarily oleic acid (OA; C18:1 n-9), such as canola oil (CO), as well as in n-3 PUFA, comprising eicosapentaenoic acid (EPA; C20:5 n-3) and docosahexaenoic acid (DHA; C22:6 n-3), which are found in abundance in marine fat sources like fish oil (FO) [13]. An adequate intake of EPA and DHA may prevent the risk of atherosclerotic cardiovascular disease [14], whereas OA consumption has been associated with vital cellular processes, involving oxidative phosphorylation and cell growth, survival, and migration [15].

From a practical feeding standpoint, the upper limit of fat supplementation in typical diets for growing-finishing pigs is 6% SO [16]. However, the effects of different fat sources compared with a standard commercial diet containing 1.5% SO have not been investigated in detail. We hypothesized that CO- and FO-based diets would improve the amount of OA, EPA, and DHA in the *longissimus lumborum* (LL) intramuscular fat, and thus enhance the nutritional and health value of pork, without adversely affecting carcass characteristics and meat quality. Therefore, this study was conducted to evaluate the effects of increasing dietary supplemental fat through different sources on growth performance, carcass characteristics, meat quality, consumer acceptability, and muscle fatty acid composition of growing-finishing pigs.

Methods

All animal procedures were approved by the “Luiz de Queiroz” College of Agriculture Animal Care and Use Committee (University of São Paulo, Piracicaba, Brazil, number CEUA 2018-28) and adhered to the Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching [17].

Animals, Experimental Design, And Housing

Ninety-six immunocastrated and halothane homozygous-negative (NN) male pigs (Large White sires x Large White dams) with an average initial body weight (BW) of 28.44 ± 2.95 kg and an average age of 71 ± 1.8 days were used in a 98-day feeding study. Pigs were randomly allotted to one of four dietary treatments with six replicate pens per treatment. Pigs were housed in an all-in/all-out double-curtain-sided building and reared in groups of four on partially slatted concrete floor pens. Overall pen size was 7.82 m^2, which provided a floor space of 1.96 m^2 per pig. Each pen was equipped with a three-hole dry self-feeder and a nipple drinker, allowing pigs *ad libitum* access to feed and water throughout the experimental period. Immunocastration of the intact males was performed by the administration of two 2-mL dose of Vivax® (Pfizer Animal Health, Parkville, Australia) at 127 and 141 days of age, in accordance with the manufacturer's recommendations. The sires and dams that originated the population used herein were genotyped for the halothane mutation (RYR1 gene) according to Fujii et al. [18].

Experimental Diets

Pigs were fed a six-phase diet that was as follows: day 0 to 21 for grower I, day 21 to 42 for grower II, day 42 to 56 for finisher I, day 56 to 63 for finisher II, day 63 to 70 for finisher III, and day 70 to 98 for finisher IV. Dietary treatments consisted of corn-soybean meal growing-finishing diets supplemented with 1.5% SO (control) or 3% fat from either SO, CO, or FO. The canola-based oil treatment used in this study was high in OA content (64.2%) and low in alpha-linolenic acid (C18:3 n-3) content (7.6%) compared to traditional CO (56.1% OA and 9.3% C18:3 n-3) available on the market as described in NRC [16]. Diets were formulated to meet or exceed the nutrient requirements of growing-finishing pigs set by Rostagno et al. [19]. Standardized ileal digestible (SID) lysine-to-metabolizable energy ratio was maintained at 3.46, 3.16, 2.86, 2.86, 2.72, and 2.71 g/Mcal for the grower-I, grower-II, finisher-I, finisher-II, finisher-III, and finisher-IV diets, respectively (Table 1). Dietary treatments within each phase were formulated to contain equal amounts of SID lysine, methionine plus cysteine, threonine, and tryptophan. Amino acid content in the diets was balanced by supplementation with crystalline amino acids to maintain the ideal pattern suggested by Rostagno et al. [19].

Table 1

Composition of the experimental diets[1] (as-fed basis)

	Grower I		Grower II		Finisher I		Finisher II		Finisher III		Finisher IV	
	(day 0 to 21)		(day 21 to 42)		(day 42 to 56)		(day 56 to 63)		(day 63 to 70)		(day 70 to 98)	
Item	Control	Fat	Control	Fat	Control	Fat	Control	Fat	Control	Fat	Control	Fat
Ingredient, %												
Corn,7.5% CP[2]	63.47	61.88	66.40	64.71	69.13	67.54	69.63	68.04	69.59	68.00	70.09	68.50
Soybean meal, 46% CP	28.33	28.42	26.10	26.29	23.37	23.46	23.37	23.46	22.93	23.02	22.93	23.02
Meat and bone meal, 44% CP	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Fat source	1.50	3.00	1.50	3.00	1.50	3.00	1.50	3.00	1.50	3.00	1.50	3.00
Dicalcium phosphate	0.55	0.56	0.56	0.57	0.26	0.27	0.26	0.27	0.27	0.27	0.26	0.27
Limestone	0.43	0.42	0.38	0.38	0.84	0.84	0.76	0.75	0.84	0.84	0.69	0.69
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin-mineral premix[3]	1.61	1.61	1.08	1.08	1.01	1.01	0.60	0.60	1.02	1.01	0.66	0.65
L-Lysine.HCl	0.35	0.35	0.29	0.29	0.25	0.25	0.25	0.25	0.20	0.20	0.20	0.20
DL-Methionine	0.11	0.11	0.07	0.08	0.04	0.04	0.04	0.04	0.02	0.02	0.03	0.03
L-Threonine	0.14	0.15	0.11	0.11	0.09	0.09	0.09	0.09	0.06	0.06	0.06	0.07
L-Tryptophan	0.01	0.01	-	-	-	-	-	-	-	-	-	-
Ractopamine.HCl, 2%	-	-	-	-	-	-	-	-	0.08	0.08	0.08	0.08
Calculated composition												
Metabolizable energy, Mcal/kg	3.28	3.36	3.29	3.36	3.28	3.36	3.29	3.36	3.28	3.35	3.29	3.36
Ether extract, %	4.02	5.45	4.05	5.48	4.10	5.53	4.10	5.53	4.11	5.54	4.11	5.54
CP, %	19.71	19.64	18.75	18.71	17.66	17.58	17.66	17.59	17.41	17.33	17.42	17.35
SID[4] Lysine, %	1.15	1.15	1.05	1.05	0.95	0.95	0.95	0.95	0.90	0.90	0.90	0.90
SID Methionine + Cysteine, %	0.62	0.62	0.57	0.57	0.51	0.51	0.51	0.51	0.49	0.49	0.49	0.49
SID Threonine, %	0.75	0.75	0.68	0.68	0.63	0.63	0.63	0.63	0.58	0.59	0.59	0.59
SID Tryptophan, %	0.22	0.22	0.20	0.20	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Calcium, %	0.84	0.84	0.81	0.81	0.80	0.80	0.77	0.77	0.80	0.80	0.75	0.75
Available Phosphorous, %	0.42	0.42	0.42	0.42	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34

[1]The added fat sources consisted of corn-soybean meal grower-finisher diets with 1.5% soybean oil (SO; control) or 3% SO, canola oil (CO), or fish oil (FO).

[2]CP = crude protein.

[3]Provided per kilogram of diet: 6.500 UI vitamin A; 1.800 UI vitamin D_3; 30 UI vitamin E; 2 mg vitamin K_3; 1.2 mg vitamin B_1; 3.4 mg vitamin B_2; 2.0 mg vitamin B_6; 125 mg Cu; 80 mg Fe; 40 mg Mn; 0.35 mg Se; 1.25 mg Zn.

[4]SID = standardized ileal digestible.

Growth Performance

Individual pig BW was measured on days 0, 21, 42, 56, 63, 70, and 98 to determine BW changes and average daily gain (ADG). All feed additions and feed remaining in the feeders at the time of pig weighing were recorded to calculate average daily feed intake (ADFI) and gain-to-feed (G:F).

Pig Slaughter And Carcass Data Collection

At the completion of the feeding trial (day 98), three pigs from each pen (n = 72; 18 pigs per treatment) were randomly chosen for slaughter to evaluate carcass and meat quality traits. Pigs were transported for approximately 503 km to a commercial pork packing plant (Frigodeliss, Capivari, SP, Brazil) and slaughtered according to the industry standards after a 16-hour rest period in the lairage pens, without feed but with free access to water. Animals were slaughtered by electrical stunning followed by exsanguination. After exsanguination, carcasses were scalded, dehaired, eviscerated, split vertically down the midline, inspected, and placed immediately into a 4 °C chill cooler. Hot carcass weight, including head and feet, was recorded at the time of slaughter to determine hot dressing percent. Chilled carcass weight was assessed 24 hours postmortem to obtain cold dressing percent. Shrink loss was calculated as the difference between hot and cold carcass weights [20]. The left carcass halves were ribbed between the 10th and 11th ribs, where the 10th-rib backfat depth was measured and the LL muscle area was outlined. The LL area was determined using the grid method. Percentage lean content of the carcasses was calculated using the equation for ribbed carcasses [21].

Meat Quality Assessment

The left side of each carcass was used to measure 45-minute and 24-hour postmortem pH on the exposed LL at the 10th rib using a HI-98163 pH meter with a stainless-steel probe (Hanna Instruments, Woonsocket, RI, USA). The left sides were then divided into primal cuts (ham, loin, belly, and shoulder) and LL sections were taken from the region of the 10th rib. Subsequently, center-cut loins were further processed into 2.5-cm-thick, trimmed of external fat and connective tissue, deboned, and used for pork quality data collection.

Drip and cooking losses were determined using the procedures outlined by Honikel [22] and AMSA [23], respectively, with modifications. Briefly, one chop from each loin section was weighed and suspended by a mesh inside an inflated and closed plastic bag. The set was placed in a chiller at 7 °C for 72 hours before being reweighed, and drip loss was calculated as a percentage of initial weight [22]. A second chop was weighed before cooking in an individual pan in a preheated 180 °C commercial oven to an internal temperature of 71 °C. The internal temperature was monitored with a hand-held digital thermometer (HM-600, Tatuapé, SP, Brazil) placed into the geometric center of each LL chop. Immediately after removal from the oven, chops were blotted dry on paper towels, allowed to cool to room temperature, and reweighed. Therefore, the difference between precooked and cooked weights was used to calculate cooking loss percentage.

The Warner-Bratzler shear force was measured as suggested by Honikel [22]. Briefly, six 1.27-cm-diameter cores from each cooked pork chop were obtained parallel to the muscle fiber orientation after chilling overnight at 4 °C. Cores were sheared once through the center using a Texture Analyzer TA-XT Plus (Stable Micro Systems, Godalming, England) attached to a Warner-Bratzler shear device with a crosshead speed of 3.33 mm/s. Samples were sheared perpendicular to the long axis of the core, and Warner-Bratzler shear force measurement was taken to be the peak force of the curve. The shear-force value for each chop was reported as the average of the shear-force values of the six cores. Finally, a third chop was vacuum-packaged and frozen at -20 °C until it was pulverized, oven-dried for 12 hours at 105 °C, and used for determination of ether extract (intramuscular fat) and fatty acid profile.

Fatty Acid Composition Analyses

Ether extract (intramuscular fat) was obtained from 5 g of LL muscle using the Soxhlet method according to AOAC [24]. For fatty acid profile determination, total lipid was isolated from 100 g of LL muscle following the cold extraction method proposed by Bligh and Dyer [25] and methylated according to the procedure outlined by AOCS [26]. Fatty acid methyl esters were quantified using a gas chromatograph (Shimadzu GC-2010 plus AF, Canby, OR, USA) equipped with a flame-ionization detector and a capillary column (Rtx-Wax, 30 m length x 0.32 mm i.d., 0.25 µm film thickness; Restek Corporation, Bellefonte, PA, USA). The temperature of the injector and of the flame-ionization detector was held constant at 250 °C and 280 °C, respectively, and the split ratio was 1:3. The flow rates were 1.2 $mL.min^{-1}$ for the carrier gas (H_2), 30 $mL.min^{-1}$ for the auxiliary gas (N_2), 30 and 300 $mL.min^{-1}$ for the flame gases H_2 and synthetic air, respectively. The column temperature was programmed to initiate at 60 °C for 4 minutes, then the temperature was raised to 210 °C at a rate of 30 $°C.min^{-1}$, held there for 7 minutes, and finally increased to 250 °C at a rate of 30 $°C.min^{-1}$ and held constant for 18 minutes. Identification of the peaks was accomplished by using a purified standard (fatty acid methyl ester mixtures, from C8 to C22) obtained from Supelco Analytical (Bellefonte, PA, USA). The results were expressed as the percentage of the normalized area of the fatty acid peak.

The total proportion of SFA was the sum of the weight percentages of myristic (C14:0), palmitic (C16:0), and stearic (C18:0) acids. The total proportion of MUFA was calculated by summing the weight percentages of palmitoleic acid (C16:1), OA, and eicosenoic acid (C20:1 n-9). Additionally, the total percentage of PUFA included C18:2 n-6, C18:3 n-3, EPA, and DHA. The sum of all n-6 PUFA, comprised only by C18:2 n-6 in our study, was divided by the sum of all n-3 PUFA (C18:3 n-3, EPA, and DHA) to calculate the n-6:n-3 PUFA ratio, whereas the PUFA:SFA ratio was calculated by dividing the total proportion of PUFA by the total proportion of SFA. From the fatty acid analysis, iodine value was calculated using the following equation: (0.95 × [C16:1]) + (0.86 × [C18:1]) + (1.732 × [C18:2]) + (2.616 × [C18:3]) + (0.785 × [C20:1]), where brackets indicate the concentration (percentage) of the fatty acid [27]. Finally, the atherogenic index was calculated by using the formula of Ulbricht and Southgate [28]: (4 × [C14:0]) + (C16:0)/(total MUFA + total PUFA), where brackets also indicate the concentration (percentage) of the fatty acid.

Representative growing-finishing diet samples were obtained from each batch and then pooled by treatment in a composite sample for fatty acid composition analysis, which was performed by the same conditions described for LL muscle (Table 2, 3, and 4).

Table 2

Fatty acid composition (%) of grower diets[1] (as-fed basis)

	Grower I (day 0 to 21)				Grower II (day 21 to 42)			
Item	Control	SO	CO	FO	Control	SO	CO	FO
Saturated fatty acid (SFA)								
Myristic acid (C14:0)	ND[2]	1.85	ND	0.24	0.24	0.31	0.16	1.53
Palmitic acid (C16:0)	13.97	12.76	10.82	20.36	13.49	14.37	10.54	18.34
Margaric acid (C17:0)	ND	ND	ND	ND	0.15	ND	ND	ND
Stearic acid (C18:0)	4.21	2.44	3.83	5.01	4.01	4.50	3.13	4.52
Arachidic acid (C20:0)	0.46	ND	0.57	0.35	0.48	0.45	0.61	0.44
Behenic acid (C22:0)	0.33	ND	0.26	0.16	0.22	0.24	0.23	ND
Monounsaturated fatty acid (MUFA)								
Palmitoleic acid (C16:1)	0.30	ND	ND	3.45	0.19	0.26	0.19	2.90
Oleic acid (C18:1 n-9)	28.97	23.27	47.52	33.16	33.21	31.92	49.72	37.65
Eicosenoic acid (C20:1 n-9)	0.27	ND	0.64	0.88	0.28	0.21	0.69	0.85
Polyunsaturated fatty acid (PUFA)								
Linoleic acid (C18:2 n-6)	47.62	55.65	32.02	29.94	45.33	44.80	33.00	30.15
Alpha-linolenic acid (C18:3 n-3)	3.57	5.85	4.31	1.62	2.41	2.95	1.74	1.47
Eicosapentaenoic acid (C20:5 n-3, EPA)	ND	ND	ND	1.06	ND	ND	ND	0.83
Docosahexaenoic acid (C22:6 n-3, DHA)	ND	ND	ND	1.78	ND	ND	ND	1.33
Total SFA	18.97	17.05	15.48	26.12	18.59	19.87	14.67	24.83
Total MUFA	29.54	23.27	48.16	37.49	33.68	32.39	50.6	41.4
Total PUFA	51.19	61.5	36.33	34.4	47.74	47.75	34.74	33.78
PUFA:SFA ratio[3]	2.70	3.61	2.35	1.32	2.57	2.40	2.37	1.36
Iodine value[4]	117.23	131.70	108.10	88.58	113.78	113.17	105.19	91.87

[1]Pigs (n = 96) were fed either a corn-soybean meal grower-finisher diets containing 1.5% soybean oil (SO; control) or diets containing 3% SO, canola oil (CO), or fish oil (FO).

[2]ND = not detectable.

[3]PUFA:SFA ratio = total PUFA/total SFA.

[4]Iodine value = (0.95 × [C16:1]) + (0.86 × [C18:1]) + (1.732 × [C18:2]) + (2.616 × [C18:3]) + (0.785 × [C20:1]), where brackets indicate concentrations [27].

Table 3

Fatty acid composition (%) of finisher diets[1] (as-fed basis)

	Finisher I (day 42 to 56)				Finisher II (day 56 to 63)			
Item	Control	SO	CO	FO	Control	SO	CO	FO
Saturated fatty acid (SFA)								
Myristic acid (C14:0)	0.29	1.87	ND[2]	ND	ND	ND	0.16	1.75
Palmitic acid (C16:0)	13.62	19.75	10.64	13.72	11.88	12.59	10.06	19.30
Margaric acid (C17:0)	ND	0.34	ND	ND	ND	ND	0.07	0.24
Stearic acid (C18:0)	4.29	4.96	3.35	4.42	3.13	2.83	2.40	4.12
Arachidic acid (C20:0)	0.43	0.43	0.57	0.35	0.42	0.41	0.58	0.36
Behenic acid (C22:0)	ND	ND	ND	0.13	0.32	0.21	0.25	ND
Monounsaturated fatty acid (MUFA)								
Palmitoleic acid (C16:1)	0.21	3.49	0.27	0.19	0.11	0.11	0.28	3.50
Oleic acid (C18:1 n-9)	35.64	36.44	52.98	35.96	30.79	34.84	52.58	36.62
Eicosenoic acid (C20:1 n-9)	ND	ND	0.71	0.78	0.20	0.23	0.73	0.92
Polyunsaturated fatty acid (PUFA)								
Linoleic acid (C18:2 n-6)	42.82	27.52	30.34	43.04	48.90	46.03	31.64	28.79
Alpha-linolenic acid (C18:3 n-3)	2.70	1.65	1.13	2.67	4.26	2.76	1.09	1.57
Eicosapentaenoic acid (C20:5 n-3, EPA)	ND	ND	ND	1.02	ND	ND	ND	1.04
Docosahexaenoic acid (C22:6 n-3, DHA)	ND	ND	ND	1.73	ND	ND	ND	1.79
Total SFA	18.63	27.35	14.56	18.62	15.75	16.04	13.52	25.77
Total MUFA	35.85	39.93	53.96	36.93	31.1	35.18	53.59	41.04
Total PUFA	45.52	29.17	31.47	48.46	53.16	48.79	32.73	33.19
PUFA:SFA ratio[3]	2.44	1.07	2.16	2.60	3.38	3.04	2.42	1.29
Iodine value[4]	112.08	86.63	101.88	113.25	122.58	117.19	103.71	89.51

[1]Pigs (n = 96) were fed either a corn-soybean meal grower-finisher diets containing 1.5% soybean oil (SO; control) or diets containing 3% SO, canola oil (CO), or fish oil (FO).

[2]ND = not detectable.

[3]PUFA:SFA ratio = total PUFA/total SFA.

[4]Iodine value = (0.95 × [C16:1]) + (0.86 × [C18:1]) + (1.732 × [C18:2]) + (2.616 × [C18:3]) + (0.785 × [C20:1]), where brackets indicate concentrations [27].

Table 4

Fatty acid composition (%) of finisher diets[1] (as-fed basis)

	Finisher III (day 63 to 70)				Finisher IV (day 70 to 98)			
Item	Control	SO	CO	FO	Control	SO	CO	FO
Saturated fatty acid (SFA)								
Myristic acid (C14:0)	0.43	0.28	0.25	1.88	ND[2]	ND	ND	1.90
Palmitic acid (C16:0)	13.61	13.82	10.71	20.02	12.90	14.45	10.60	20.11
Margaric acid (C17:0)	ND	0.16	0.13	ND	ND	ND	ND	ND
Stearic acid (C18:0)	4.98	4.28	3.61	5.06	3.81	4.53	3.39	4.73
Arachidic acid (C20:0)	0.40	0.43	0.54	ND	ND	0.43	0.58	ND
Behenic acid (C22:0)	ND	0.19	0.26	ND	ND	ND	ND	ND
Monounsaturated fatty acid (MUFA)								
Palmitoleic acid (C16:1)	0.54	0.32	0.24	3.52	ND	0.22	0.39	3.61
Oleic acid (C18:1 n-9)	33.32	34.95	48.67	36.77	30.18	35.58	52.26	35.44
Eicosenoic acid (C20:1 n-9)	0.32	0.26	0.62	ND	0.42	ND	0.71	0.90
Polyunsaturated fatty acid (PUFA)								
Linoleic acid (C18:2 n-6)	42.63	42.85	33.47	28.41	48.53	42.56	30.99	28.92
Alpha-linolenic acid (C18:3 n-3)	3.78	2.45	1.51	1.52	4.16	2.24	1.07	1.55
Eicosapentaenoic acid (C20:5 n-3, EPA)	ND	ND	ND	1.05	ND	ND	ND	1.07
Docosahexaenoic acid (C22:6 n-3, DHA)	ND	ND	ND	1.78	ND	ND	ND	1.77
Total SFA	19.42	19.16	15.5	26.96	16.71	19.41	14.57	26.74
Total MUFA	34.18	35.53	49.53	40.29	30.6	35.8	53.36	39.95
Total PUFA	46.41	45.3	34.98	32.76	52.69	44.8	32.06	33.31
PUFA:SFA ratio[3]	2.39	2.36	2.26	1.22	3.15	2.31	2.20	1.25
Iodine value[4]	113.14	111.19	104.49	88.15	121.22	110.38	102.35	88.76

[1]Pigs (n = 96) were fed either a corn-soybean meal grower-finisher diets containing 1.5% soybean oil (SO; control) or diets containing 3% SO, canola oil (CO), or fish oil (FO).

[2]ND = not detectable.

[3]PUFA:SFA ratio = total PUFA/total SFA.

[4]Iodine value = (0.95 × [C16:1]) + (0.86 × [C18:1]) + (1.732 × [C18:2]) + (2.616 × [C18:3]) + (0.785 × [C20:1]), where brackets indicate concentrations [27].

Overall Liking

The chops were thawed at 4 °C overnight before cooking on an electric grill to an internal temperature of 71 °C, which was monitored by individual thermometers inserted into the center of each chop. Subsequently, cooked chops were cut into 10 g cubes and wrapped with aluminum foil to avoid temperature loss during serving. The consumer tests were carried out in individual booths under artificial white light. The samples were placed in 50 mL disposable plastic cups, coded with three-digit random numbers, and served in a sequential monadic order according to a Williams Latin square design. Filtered water and crackers were served as palate cleansers in-between samples. The panel consisted of 101 regular pork consumers (60% females and 40% males, age ranged from 18 to 65 years old), which were recruited from students and staffs of the “Luiz de Queiroz” College of Agriculture, University of São Paulo. In a single session, each panelist evaluated the four treatments (one sample per treatment) for overall liking using a nine-point hedonic scale (1 = extremely dislike; 5 = neither like nor dislike; 9 = extremely like) [29]. Data were collected by Compusense Cloud (Compusense Inc., Guelph, ON, Canada) using tablets (Samsung Galaxy Table E, T560, screen 9.6"). All consumer panelists filled out a consent form, which was previously approved by the Ethics Committee of the “Luiz de Queiroz” College of Agriculture (University of São Paulo, Piracicaba, Brazil, number CAAE 04352718.6.0000.5395).

Statistical Analyses

Excepted for overall liking, all other data were analyzed as a randomized complete block design using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) for repeated measures, and pen was considered the experimental unit. Outliers were removed from the data sets and residuals were tested for a normal

distribution using the Shapiro-Wilk test (UNIVARIATE procedure). Non-normally distributed data were log-transformed for analysis and back-transformed for presentation. Growth performance data were analyzed as repeated measures over time, and the model included dietary treatment, time, and the two-way interaction as the fixed effects, block and pen as the random effects, and pen (nested within treatment) as the subject of the REPEATED statement. For each analyzed variable, data were subjected to five covariance structures: variance components, compound symmetry, first-order autoregressive, heterogeneous first-order autoregressive, and unstructured. The covariance structure that yielded the smallest Bayesian information criterion (BIC) was used for the results presented. For carcass characteristics, meat quality, and fatty acid composition data, dietary treatment and block were included as the fixed and random effects, respectively, in the model. The LSMEANS option was used to generate treatment means, which were separated using the PDIFF option based on Student's *t* test. Significance was declared at $P \leq 0.05$, and trends were discussed at $0.05 < P \leq 0.10$. Data from overall liking were analyzed by the non-parametric Friedman test at 5% probability.

Results

Growth performance

There were no pig mortalities throughout the experiment. Including either 1.5% SO or 3% fat, regardless of source, in the diets of growing-finishing pigs did not alter growth performance from day 0 to 21, day 21 to 42, day 42 to 56, and day 70 to 98 (Table 5). Although ADG and G:F did not differ among treatments from day 56 to 63, pigs fed diets containing 3% SO tended to have increased ADFI ($P = 0.10$) when compared with those fed the control diet. From day 63 to 70, pigs fed diets containing either 3% SO or FO grew faster ($P = 0.03$) and had greater ADFI ($P < 0.01$) than those fed the control diet, but G:F was similar for all treatment groups. Overall ADG and G:F were not affected by dietary fat source. Compared to the control diet, there was a trend for greater overall ADFI ($P = 0.07$) and increased BW on day 98 ($P = 0.09$) when 3% CO was added to the diet.

Table 5

Effects of dietary treatments on growth performance of growing-finishing pigs[1]

Item[2]	Dietary treatment				Pooled SEM[3]	*P*-value
	Control	SO	CO	FO		
BW, kg						
day 0	27.32	28.78	29.56	28.10	0.602	0.86
day 21	44.29	45.71	47.33	44.50	0.938	0.65
day 42	61.65	63.42	65.46	62.21	1.204	0.50
day 56	78.07	79.29	81.75	79.58	1.301	0.58
day 63	87.25	88.75	91.25	88.79	1.279	0.51
day 70	95.40	98.67	100.21	98.42	1.543	0.34
day 98	129.90^{b}	132.13^{ab}	136.63^{a}	133.00^{ab}	1.593	0.09
Grower I (day 0 to 21)						
ADG, kg	0.809	0.806	0.847	0.781	0.020	0.91
ADFI, kg	1.431	1.426	1.475	1.455	0.032	0.98
G:F	0.565	0.566	0.575	0.537	0.008	0.59
Grower II (day 21 to 42)						
ADG, kg	0.827	0.843	0.863	0.843	0.021	0.98
ADFI, kg	1.838	1.917	1.953	1.872	0.035	0.80
G:F	0.450	0.441	0.442	0.450	0.007	0.98
Finisher I (day 42 to 56)						
ADG, kg	1.173	1.134	1.164	1.241	0.028	0.69
ADFI, kg	2.369	2.493	2.447	2.516	0.043	0.64
G:F	0.495	0.451	0.475	0.496	0.008	0.36
Finisher II (day 56 to 63)						
ADG, kg	1.312	1.351	1.357	1.315	0.034	0.94
ADFI, kg	2.694^{b}	2.982^{a}	2.912^{ab}	2.926^{ab}	0.046	0.10
G:F	0.489	0.454	0.468	0.453	0.013	0.58
Finisher III (day 63 to 70)						
ADG, kg	1.165^{b}	1.417^{a}	1.280^{ab}	1.375^{a}	0.062	0.03
ADFI, kg	2.644^{b}	3.037^{a}	2.717^{b}	2.960^{a}	0.068	< 0.01
G:F	0.435	0.468	0.469	0.455	0.015	0.61
Finisher IV (day 70 to 98)						
ADG, kg	1.232	1.195	1.301	1.235	0.019	0.71
ADFI, kg	3.136	3.276	3.201	3.186	0.045	0.72
G:F	0.394	0.365	0.407	0.388	0.006	0.53
Overall (day 0 to 98)						
ADG, kg	1.003	1.055	1.093	1.070	0.017	0.79

[1]Pigs (n = 96) were fed either a corn-soybean meal diet containing 1.5% soybean oil (SO; control) or diets containing 3% SO, canola oil (CO), or fish oil (FO). Values represent the least square means of 6 replicate pens and 4 pigs per pen.

[2]BW, body weight; ADG, average daily gain; ADFI, average daily feed intake; G:F, gain-to-feed.

[3]SEM = standard error of the least square means.

[a,b]Within a row, values without a common superscript differ ($P \leq 0.05$) or tended to differ ($0.05 < P \leq 0.10$) using Tukey's method.

Item[2]	Dietary treatment				Pooled SEM[3]	*P*-value
	Control	SO	CO	FO		
ADFI, kg	2.333[b]	2.438[ab]	2.622[a]	2.403[ab]	0.051	0.07
G:F	0.432	0.433	0.424	0.446	0.008	0.89

[1]Pigs (n = 96) were fed either a corn-soybean meal diet containing 1.5% soybean oil (SO; control) or diets containing 3% SO, canola oil (CO), or fish oil (FO). Values represent the least square means of 6 replicate pens and 4 pigs per pen.

[2]BW, body weight; ADG, average daily gain; ADFI, average daily feed intake; G:F, gain-to-feed.

[3]SEM = standard error of the least square means.

[a,b]Within a row, values without a common superscript differ ($P \leq 0.05$) or tended to differ ($0.05 < P \leq 0.10$) using Tukey's method.

Carcass And Meat Quality Traits

There were no effects of dietary fat source on BW at slaughter, as well as on hot and cold carcass weights (Table 6). However, carcasses from pigs fed 3% SO tended to have greater hot dressing percent (P = 0.07) and had greater cold dressing percent (P = 0.04) than carcasses from pigs fed the control diet or diets supplemented with 3% CO or FO. Shrink loss, loin eye area, LL intramuscular fat, 10th-rib backfat, and lean percentage were not altered by the dietary treatments. Loins from pigs fed diets containing either 3% SO or CO showed a decrease in Warner-Bratzler shear force (P = 0.05) when compared to loins from control-fed pigs. No additional meat quality traits were altered by the dietary treatments (Table 6).

Table 6

Effects of dietary treatments on carcass characteristics and *longissimus lumborum* (LL) muscle quality of growing-finishing pigs[1]

Item	Dietary treatment				Pooled SEM[2]	*P*-value
	Control	SO	CO	FO		
Slaughter weight, kg	129.60	131.16	136.61	132.44	1.61	0.51
Hot carcass weight, kg	98.21	99.72	102.70	99.53	1.20	0.54
Cold carcass weight, kg	91.03	92.53	95.42	92.37	1.17	0.55
Hot dressing percent,[3] %	75.18[b]	76.03[a]	75.20[b]	75.23[b]	0.14	0.07
Cold dressing percent,[4] %	69.65[b]	70.53[a]	69.86[b]	69.74[b]	0.14	0.04
Shrink loss,[5] %	7.35	7.24	7.11	7.30	0.06	0.48
10th-rib backfat, mm	18.95	19.17	18.31	19.95	0.61	0.80
Lean percentage,[6] %	56.42	55.32	56.02	55.09	0.25	0.16
LL						
Area, cm^2	56.72	53.74	56.68	53.60	0.86	0.40
Intramuscular fat, %	1.94	2.63	2.19	2.65	0.19	0.34
pH at 45 minutes	6.24	6.33	6.24	6.27	0.02	0.39
pH at 24 hours	5.72	5.78	5.79	5.69	0.02	0.42
Drip loss, %	5.59	4.94	5.82	4.88	0.24	0.46
Cooking loss, %	18.71	17.89	19.09	17.74	0.46	0.47
Warner-Bratzler shear force, N	46.34[a]	34.73[b]	35.66[b]	40.81[ab]	0.18	0.05

[1]Pigs ($n = 96$) were fed either a corn-soybean meal diet containing 1.5% soybean oil (SO; control) or diets containing 3% SO, canola oil (CO), or fish oil (FO). Values represent the least square means from a subset of pigs ($n = 72$; 18 pigs/treatment).

[2]Standard error of the least square means.

[3]Hot dressing percent = {(hot carcass weight/slaughter weight)} × 100.

[4]Cold dressing percent = {(cold carcass weight/slaughter weight)} × 100.

[5]Shrink loss = {1- (cold carcass weight/hot carcass weight)} × 100 [20].

[6]Lean percentage = {[7.231 + (0.437 × hot carcass weight, lb.) − (18.746 × 10th-rib backfat, in.) + (3.877 × LL area, sq. in.)]/hot carcass weight, lb.} × 100 [21].

[a,b]Within a row, values without a common superscript differ ($P \leq 0.05$) or tended to differ ($0.05 < P \leq 0.10$) using Tukey's method.

Fatty Acid Composition Of LL Intramuscular Fat

Feeding diets with different fat sources did not influence the percentages of C14:0 and C20:1 n-9 in the LL intramuscular fat (Table 7). Compared to all other diets, FO-enriched diets led to the greatest ($P < 0.01$) percentages of C16:0, C18:0, EPA, and DHA. The LL intramuscular fat from pigs fed 3% FO had the greatest ($P < 0.01$) degree of saturation (40.29% SFA), but also had the lowest n-6:n-3 PUFA ratio ($P < 0.01$). Feeding pig diets that contained 3% SO or CO resulted in greater ($P < 0.01$) proportions of OA and total MUFA than control- or FO-fed pigs. On the other hand, LL intramuscular fat from SO- or CO-fed pigs had the lowest proportion of total n-3 PUFA ($P < 0.01$). Adding 3% dietary fat, regardless of source, decreased ($P < 0.01$) the percentages of C18:2 n-6 and C18:3 n-3, total PUFA, PUFA:SFA ratio, and total n-6 PUFA compared with control-fed pigs. The proportion of C16:1 was greatest ($P = 0.04$) in the intramuscular loin fat from SO- and FO-fed pigs, whereas the atherogenic index was increased ($P < 0.01$) in the muscle of FO-fed pigs. Pigs fed the control diet had a greater iodine value ($P = 0.02$) in the LL intramuscular fat than pigs fed all other diets.

Table 7

Effects of dietary treatments on fatty acid composition (%) of *longissimus lumborum* intramuscular fat of growing-finishing pigs[1]

Item	Dietary treatment				Pooled SEM[2]	*P*-value
	Control	SO	CO	FO		
Saturated fatty acid (SFA)						
Myristic acid (C14:0)	1.14	1.19	1.21	1.24	0.01	0.11
Palmitic acid (C16:0)	25.50^{b}	25.01^{b}	24.70^{b}	26.43^{a}	0.21	< 0.01
Stearic acid (C18:0)	12.02^{b}	11.89^{b}	11.04^{c}	12.63^{a}	0.15	< 0.01
Monounsaturated fatty acid (MUFA)						
Palmitoleic acid (C16:1)	2.86^{b}	3.17^{a}	3.05^{ab}	3.26^{a}	0.05	0.04
Oleic acid (C18:1 n-9)	38.92^{b}	44.60^{a}	44.95^{a}	40.33^{b}	0.64	< 0.01
Eicosenoic acid (C20:1 n-9)	0.51	0.56	0.58	0.56	0.01	0.21
Polyunsaturated fatty acid (PUFA)						
Linoleic acid (C18:2 n-6)	17.90^{a}	12.96^{b}	13.33^{b}	13.83^{b}	0.50	< 0.01
Alpha-linolenic acid (C18:3 n-3)	0.80^{a}	0.54^{b}	0.53^{b}	0.59^{b}	0.03	< 0.01
Eicosapentaenoic acid (C20:5 n-3, EPA)	0.29^{b}	0.11^{c}	0.08^{c}	0.46^{a}	0.04	< 0.01
Docosahexaenoic acid (C22:6 n-3, DHA)	0.36^{b}	0.14^{c}	0.09^{c}	0.61^{a}	0.05	< 0.01
Total SFA	38.83^{b}	38.09^{b}	37.44^{b}	40.29^{a}	0.33	< 0.01
Total MUFA	41.78^{b}	47.32^{a}	48.76^{a}	43.55^{b}	0.68	< 0.01
Total PUFA	18.91^{a}	13.74^{b}	13.97^{b}	15.60^{b}	0.54	< 0.01
Total n-3 PUFA[3]	1.01^{a}	0.70^{b}	0.64^{b}	1.39^{a}	0.08	< 0.01
Total n-6 PUFA[4]	17.90^{a}	12.96^{b}	13.33^{b}	13.83^{b}	0.50	< 0.01
PUFA:SFA ratio[5]	0.46^{a}	0.36^{b}	0.37^{b}	0.38^{b}	0.01	< 0.01
n-6:n-3 PUFA ratio[6]	18.98^{a}	18.93^{a}	21.67^{a}	11.87^{b}	0.92	< 0.01
Iodine value[7]	69.12^{a}	65.41^{b}	66.49^{b}	64.49^{b}	0.59	0.02
Atherogenic index[8]	0.50^{b}	0.49^{b}	0.48^{b}	0.53^{a}	0.01	0.02

[1]Pigs (n = 96) were fed either a corn-soybean meal diet containing 1.5% soybean oil (SO; control) or diets containing with 3% SO, canola oil (CO), or fish oil (FO). Values represent the least square means from a subset of pigs (n = 72; 18 pigs/treatment).

[2]SEM = standard error of the least square means.

[3]Total n-3 PUFA = {[C18:3 n-3] + [C20:5 n-3] + [C22:6 n-3]}.

[4]Total n-6 PUFA = C18:2 n-6.

[5]PUFA:SFA ratio = total PUFA/total SFA.

[6]Σ n-6/Σ n-3 PUFA ratio.

[7]Iodine value = (0.95 × [C16:1]) + (0.86 × [C18:1]) + (1.732 × [C18:2]) + (2.616 × [C18:3]) + (0.785 × [C20:1]), where brackets indicate concentrations [27].

[8]Atherogenic index = (4 × [C14:0]) + (C16:0)/(total MUFA] + [total PUFA]), where brackets indicate concentrations [28].

[a–c]Within a row, values without a common superscript differ ($P \leq 0.05$) or tended to differ ($0.05 < P \leq 0.10$) using Tukey's method.

Overall liking

Loin chops from pigs fed diets that contained 3% SO had greater consumer overall liking score ($P < 0.001$) when compared with chops from pigs fed the control diets or diets formulated with 3% FO, whereas the addition of 3% CO to growing-finishing pig diets resulted in loin chops with similar consumer overall liking rating compared to chops from all other dietary treatments (Fig. 1).

Discussion

Fat-supplemented diets are an important nutritional strategy aimed at improving pig productivity. However, high-fat diets (i.e. more than 6% added fat) are rather impractical for pig feeding systems used by most producers because they promote reduction of carcass leanness, as well as feed processing and handling issues [16, 30]. In commercial pig production, diets are commonly formulated with 1.5% SO for growing-finishing pigs. Although a wide range of studies have been conducted to evaluate diets with varying levels of supplemental fat, information concerning different dietary fat sources and inclusion level in commercial pig production is scarce. Therefore, our study was designed to investigate the effects of increasing dietary supplemental fat from different sources on growth performance, carcass characteristics, meat quality, consumer acceptability, and intramuscular fatty acid composition of growing-finishing pigs.

Fats and oils play an essential role in feed choice related to taste perception [31]. Feeding diets containing 3% CO resulted in a tendency towards increased overall feed intake and, consequently, heavier pigs over the entire growing-finishing period compared with those fed a standard commercial diet containing 1.5% SO. Others have reported no effect of CO on feed intake in growing-finishing pigs when added at 3% [32] or at 5 or 10% [33] of the diets. Interestingly, the greater the degree of unsaturation of the fatty acids in dietary fat, the more vulnerable it is to rancidity, thus reducing the consumer acceptability value [34]. In our study, however, diets containing 3% CO showed the best preference value, even though unsaturated fatty acids made up 85.01% of the total fatty acids in this diet.

Adding 3% SO, CO, or FO did not alter overall weight gain and feed efficiency of growing-finishing pigs in comparison with the addition of 1.5% SO. These findings are similar to those reported in a previous study, in which including 5% fat as either SO, beef tallow, or poultry fat did not affect any growth responses across the entire feeding trial [35]. In contrast, Weber et al. [36] reported that pigs fed 5% added fat as either choice white grease or beef tallow exhibited decreased ADFI and increased G:F. Adding 6% SO, choice white grease, or animal-vegetable fat blend to pig diets have been associated with improved growth rate and efficiency of feed utilization [3, 37]. As reviewed by Moser [37], weight gain responses are inconsistent when adding up to 5% fat to growing-finishing pig diets, whereas remarkable improvements in feed efficiency are observed at levels ranging from 2 to 20% added fat.

Similar to overall growth performance, no differences were noted for carcass characteristics across dietary treatments, except for dressing percent. Inconsistent with the previous studies [32, 39, 40], the results of the present study demonstrated that formulating growing-finishing pig diets with 3% SO tended to increase hot dressing percent and increased cold dressing percent. As heavier or fatter carcasses positively influence dressing percent [41], our results were not expected, considering no treatment differences were observed on BW at slaughter, hot and cold carcass weights, loin eye area, and 10th-rib backfat.

It is well accepted that intramuscular fat content directly affects tenderness and overall preference [42]. In fact, many studies have suggested a significant correlation between intramuscular fat (i.e. marbling) and pork tenderness, in which increases in marbling scores are accompanied by either an increase in tenderness or a decrease in Warner Bratzler shear force [43–45]. However, regarding the influence of dietary fat supplementation on intramuscular fat content of growing-finishing pigs, there is no general consensus [32].

Our results indicate that loins from pigs fed diets that contain either 3% SO or CO had reduced Warner-Bratzler shear force compared to loins from pigs fed a standard commercial diet formulated with 1.5% SO. However, the majority of the results reported in the literature diverge from our findings, as Warner-Bratzler shear force of pork loin was not affected by formulating diets with 2 or 5% CO or beef tallow [46], 5% SO or beef tallow [47], 3% different fat sources, including beef tallow, coconut oil, olive oil, and SO [48], or 3% of a blend of coconut oil and CO [49]. In this way, given that the intramuscular fat content in the LL muscle did not differ among treatments in the current experiment, the reason for the increased pork tenderness by feeding pig diets containing either 3% SO or CO remains unclear.

It is well established that tenderness is likely the most important meat palatability trait, as consumers are more able to identify differences in tenderness than in juiciness and flavor [50]. In the current study, the addition of 3% SO to growing-finishing pig diets resulted in loin chops that were rated higher for consumer preference. This could likely be ascribed to the fact that these loins were more tender, as indicated by their reduced Warner-Bratzler shear force values, than those from all other dietary treatment. Moreover, it has been previously reported that feeding 3% FO to pigs resulted in increased pork off-flavor and off-odor than feeding 3% SO, thereby limiting its acceptance [51].

By adding 3% CO to the diet, OA and total MUFA concentrations in the LL intramuscular fat were slightly increased compared with pigs fed the control diet, which is in agreement with the results observed by Myer et al. [33]. The lack of a major increase may be explained by the high levels of MUFA that naturally occur in pork muscle [11]. In addition, fatty acids profile in animal tissues is primarily affected by both *de novo* synthesis and dietary fat intake [52]. In pigs, even though the diet accounts for a notable level of OA in adipose tissue, *de novo* synthesis is still the preferred MUFA pathway supply to the body, hence its tissue content is less readily influenced by the diet [1, 53]. For this reason, an increased desaturation activity of 18:0 into OA by stearoyl-CoA desaturases might have occurred in our study, thus increasing MUFA content via *de novo* synthesis [54]. Beneficial effects of MUFA-rich diets on blood lipid profiles and cardiovascular disease risk factors, including hypertension and obesity, have been received considerable attention during recent years [55, 56].

Diets formulated with 3% FO, which were characterized by a greater SFA, EPA, and DHA contents among all dietary treatments, raised the levels of SFA, C16:0 and C18:0 in particular, as well as the levels of the aforementioned long chain n-3 PUFA in the LL muscle lipids of pigs. These results were expected, given that fatty acids absorbed from the diet, especially essential PUFA such as EPA and DHA, which cannot be synthesized by animal tissues [1]. Moreover, our findings indicate that dietary n-3 PUFA are more preferentially deposited in intramuscular loin fat than is C18:2 n-6 when the fat source fed is FO, as previously described by Irie and Sakimoto [57].

Opposed to the results observed in the current study, similar changes in the amount of C16:0 and C18:0 in porcine carcass fat as dietary FO addition increased from 0 to 6% were not observed by Irie and Sakimoto [57]. These discrepancies could be partly attributed to differences in the feeding duration of the supplemental marine fat. In our study, pigs were fed dietary FO over the entire 14-week growing-finishing period, whereas Irie and Sakimoto [57] used diets with added FO for only four weeks prior to slaughter. Our findings were consistent with those of Apple et al. [35], who demonstrated that the alterations in SFA content in porcine muscle were detected when dietary fat sources were fed for periods greater than six to eight weeks before slaughter.

The present observation that feeding a standard diet with 1.5% SO increased the proportions of C18:2 n-6, C18:3 n-3, total n-6 PUFA, total PUFA, and PUFA:SFA ratio in the LL intramuscular fat more than all other diets rich in fat, regardless of source, conforms with the results of Bertol et al. [32]. However, our findings are remarkably different from those previously reported by Averette Gatlin et al. [58], in which the proportions of C18:2 n-6 in the intramuscular loin fat were not altered by dietary fat composition, opposing to belly and backfat depots. Because pigs do not synthesize C18:2 n-6 and C18:3 n-3, intramuscular loin fat reflects the contribution of those fatty acids from the dietary fat consumed [1]. Even though structural fat, which is abundant in the muscle but not in belly fat or backfat, does not respond rapidly to dietary changes when compared with the depot fat [59], the results from this study indicate that the dietary inclusion of 1.5% SO is adequate enough to alter LL intramuscular fatty acid composition in growing-finishing pigs.

Interestingly, an increase in the proportion of C18:2 n-6 with a concomitant reduction in OA content were observed in the LL intramuscular fat from pigs that consumed diets supplemented with 1.5% SO, but not with 3% added SO. This inverse relationship between C18:2 n-6 and OA has also been observed in the backfat of growing-finishing pigs [60]. Whittington et al. [61] demonstrated that the proportions of C18:2 n-6 and OA in porcine backfat are inversely correlated; thus, one might speculate that this relationship between C18:2 n-6 and OA also occurs in the intramuscular loin fat of pigs. Additionally, one possible reason for the reduced proportions of C18:2 n-6 and total PUFA found in the LL intramuscular fat of pigs fed 3% added SO is that, at the higher dietary OA concentration observed for that treatment, OA and C18:2 n-6 could have competed for incorporation into the LL muscle fat, thus favoring OA deposition at the expense of C18:2 n-6 [62].

Based on the recommendation for a healthy human diet, the minimum acceptable PUFA:SFA ratio should be 0.4, whereas the n-6:n-3 PUFA ratio should be less than 5 [63]. According to Čítek et al. [64], porcine intramuscular fat generally exhibits PUFA:SFA ratio of approximately 0.3 and values of n-6:n-3 PUFA ratio ranging from 9 to 12. Pigs fed the control diet had increased PUFA:SFA ratio of 0.46 in the LL intramuscular fat compared with pigs fed 3% added fat, regardless of source, that showed an average value of 0.37, which is rather unfavorable from a human health perspective. Additionally, even though pigs fed 3% FO showed the lowest n-6:n-3 PUFA ratio in the LL intramuscular fat in comparison with pigs fed all other diets, the n-6:n-3 PUFA ratio for all dietary treatments far exceeded the recommendation.

Iodine value is a measure of the degree of unsaturation of fatty acids in a lipid sample [60]. Because SO has higher C18:2 n-6 concentration than most vegetable oils used in commercial swine diets, it would be expected that pigs fed 3% SO had a greater iodine value than those fed the control diet. However, the opposite response was found in our experiment, as the iodine value of LL intramuscular fat from pigs fed a standard commercial diet with 1.5% SO was increased by approximately 4 percentage units when compared to all other fat-rich diets. In spite of that, our findings indicate that the iodine value of the LL intramuscular fat may be altered by careful selection of dietary fat sources fed to growing-finishing pigs. Our results from the LL intramuscular fat analysis are in agreement with previous observations, in which the iodine value increased when SO was included at 3% [32] or 5% [35] in the diet of growing-finishing pigs.

The atherogenic index represents the overall dietetic quality of lipids and their potential effects on the development of cardiovascular disease [65]. Intramuscular fat from the LL of pigs fed 3% FO showed a greater atherogenic index likely due to an increased proportion of C16:0. Except for the FO-rich diet, which had the atherogenic index exceeding the set limit of 0.5, all other dietary treatments exhibited values close to the recommended maximum [28]. Therefore, our results suggest that the dietary supplementation of 3% FO for growing-finishing pigs does not appear to be desirable from a consumer health standpoint.

Conclusions

Feeding growing-finishing pig diets containing 3% of a fat source as SO, CO, or FO did not alter overall growth performance and carcass characteristics. This research also demonstrated that the fatty acid composition of the intramuscular LL muscle was altered by all dietary fat sources. Although adding 3% CO or FO to pig diets provided slight nutritional benefits to consumers in terms of MUFA and long chain n-3 PUFA contents, respectively, formulating growing-finishing diets with 1.5% SO was adequate enough in terms of LL intramuscular fatty acids composition for high quality meat destined to human consumption. However, panelists favored loins from pigs fed diets with 3% SO, likely because of the improved pork tenderness. A better understanding of the metabolic alterations that occur with the dietary inclusion of those fat sources and the related signaling pathways may optimize pig feeding regimens involving either fat sources or levels for managing the undesirable health outcomes, such as obesity.

Abbreviations

ADFI: average daily feed intake; ADG: average daily gain; BW: body weight; CO: canola oil; DHA: docosahexaenoic acid (C22:6 n-3); EPA: eicosapentaenoic acid (C20:5 n-3); FO: fish oil; G:F: gain-to-feed; LL: *longissimus lumborum*; MUFA: monounsaturated fatty acids; OA: oleic acid (C18:1 n-9); PUFA: polyunsaturated fatty acids; SID: standardized ileal digestible; SFA: saturated fatty acids; SO: soybean oil.

Declarations

Ethics approval and consent to participate

The study was carried out in accordance with the Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching, and received prior approval by the “Luiz de Queiroz” College of Agriculture Animal Care and Use Committee (University of São Paulo, Piracicaba, Brazil, number CEUA 2018-28). All consumer panelists filled out a consent form, which was previously approved by the Ethics Committee of the “Luiz de Queiroz” College of Agriculture (University of São Paulo, Piracicaba, Brazil, number CAAE 04352718.6.0000.5395).

Consent for publication

Not applicable.

Availability of data and material

The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

VVA: formal analysis, writing-original draft, writing-review and editing, and visualization. JPMS: physicochemical and sensory analyses. ANM: formal analysis, methodology and writing-review and editing. GCMM: formal analysis, methodology and writing-review and editing. JDG: physicochemical and sensory analyses. MDP: formal analysis, methodology and writing-review and editing. MDBD: physicochemical and formal analyses. IP: sensory analysis. CJCC: conceptualization, writing-review and editing. LLC: conceptualization, formal analysis, writing-review and editing. GBM: formal analysis, writing-review and editing. JMR: conceptualization, writing-review and editing. DK: conceptualization, formal analysis, writing-review and editing. NVLS: conceptualization, formal analysis, writing-review and editing. LCAR: conceptualization, formal analysis, writing-review and editing. HF: conceptualization, formal analysis, writing-review and editing. APLB: diet formulation, writing-review and editing. SMA: fatty acid profile analysis, writing-review and editing. ALF: carcass and meat quality evaluation, formal analysis. ASMC: conceptualization, experimental design, funding acquisition, project administration, formal analysis, writing-original draft, writing-review and editing. All authors read and approved the final manuscript.

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Figures

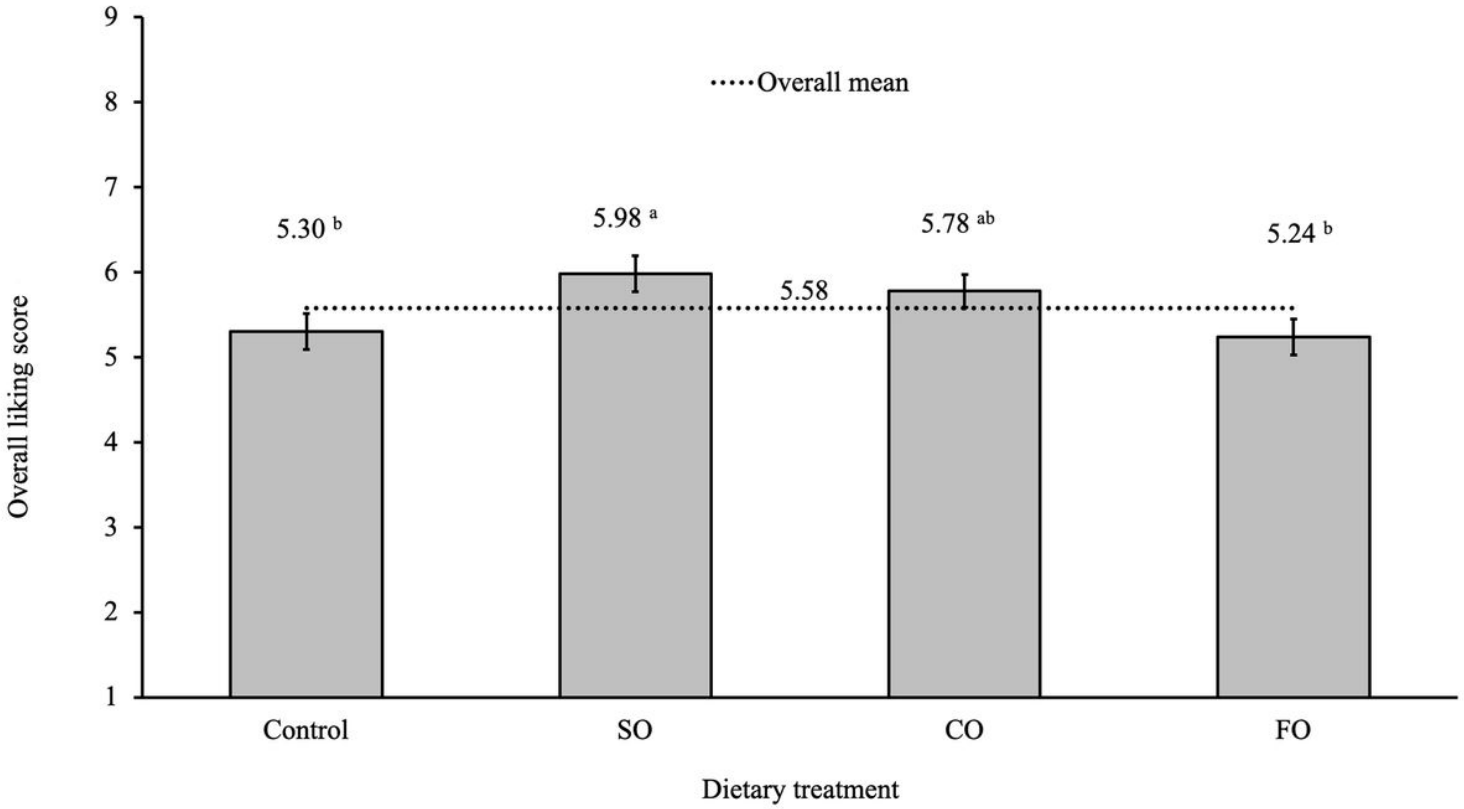

Figure 1

Overall liking of longissimus lumborum (LL) muscle from pigs fed diets containing either 1.5% soybean oil (SO; control) or 3% SO, canola oil (CO), or fish oil (FO). Values represent means ± SEM. a-bMeans with different superscript letters differ ($P < 0.05$).