Use of pure glycerol in fattening heavy pigs ☆

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ABSTRACT

Eighty Italian Duroc × Italian Large White pigs (BW 42.6 ± 3.37 kg) were used to determine the effects of pure glycerol on growth performance and meat quality of heavy pigs. Pigs were divided into five groups receiving 0% (control), 5% or 10% during the growing and finishing phases (42.6–160 kg BW) (G+F5,G+F10) or 5% or 10% during the finishing period (100–160 kg BW) (FIN5,FIN10) of pure glycerol in substitution for maize meal (on a dry matter basis). The pigs were slaughtered at approximately 160 kg BW. The growth performance of pigs fed 5% glycerol did not differ from controls regardless of feeding duration, whereas those fed 10% glycerol showed reduced growth and poorer feed:gain ratio. Fat quality and meat suitability for raw ham curing were not affected by dietary treatment. Differences were not consistent enough to draw any conclusion about the effects of feeding glycerol on sensory characteristics.

1. Introduction

Glycerine (crude glycerol) is the main by-product of biodiesel production. According to Thompson and He (2006), 79 g of crude glycerine are generated for every litre of biodiesel produced. EC Directive 2003/30 states that by 31 December 2010, biofuels should account for 5.75% of all petrol and diesel for transport purposes. The Commission Green Paper "Towards a European strategy for the security of energy supply" sets the objective of 20% substitution of conventional fuels by alternative fuels in the road transport sector by 2020 (Commission Green Paper, 2001).

Therefore, it may be argued that in the near future a large amount of crude glycerol will be available in Europe. According to Thompson and He (2006) glycerol, when refined to a chemically pure substance, would be a very valuable by-product with hundreds of uses. Purifying it to that stage, however, is very costly and generally not economically feasible for small to medium sized plants. These size plants may represent the future of Italian biodiesel production to reduce harvesting and related costs of raw material transport (Riva, Foppa Pedretti, & Toscano, 2007). Animal feeding may be an alternative utilization for crude glycerol if a suf-

ficient degree of purity could be achieved with less expensive refining systems.

In the last two decades some trials have been conducted on the use of crude glycerol in growing/finishing pigs (Cerneau, Mourot, & Peyronnet, 1994; Kijora & Kupsch 1996; Kijora, Kupsch, Bergner, Wenk, & Prabucki, 1997; Lammers et al., 2007; Mourot, Aumaitre, Mounier, Peiniau, & François, 1994). Mourot et al. (1994) found that 5% of crude glycerol in diets with added animal or vegetable fat leads to a reduction of drip and cooking loss in *longissimus dorsi* and *semimembranosus* muscles. These data are consistent with the results of Cerneau et al. (1994), who found an increased yield in cooked ham production using thighs of pigs which had been fed glycerol. Kijora and Kupsch (1996) found that both pure and crude glycerol had no effects on meat quality, even though they found a tendency toward a reduction in drip and press water loss. Mourot et al. (1994) also found an increase in the percentage of oleic acid and a decrease in the percentages of linoleic and linolenic acid in subcutaneous fat. These findings partially agree with the results of Cerneau et al. (1994), identifying an increase in the percentage of palmitic acid and a decrease in linoleic acid, and the results of Kijora et al. (1997), showing a tendency towards an increase of oleic acid, a decrease of stearic acid and a significant reduction of linoleic acid content.

Both subcutaneous fat fatty acid composition and ham water loss during curing are important parameters for the production of heavy pigs, whose thighs are utilized for the production of the typical raw hams of Northern Italy. To avoid soft and oily

subcutaneous fat, the Parma Ham production rules provide that the content of linoleic fatty acid must not exceed 15%, and the Iodine value must not exceed 70. Thereafter, each polyunsaturated fatty acid reduction must be considered favourable for raw ham quality. The water loss (and related salt absorption) during the salting period, the first phase of cured ham production, is important both for the organoleptic and dietetic qualities of ham and for its improved storage. In fact, excessive water loss increases the saltiness and toughness in cured hams, whereas insufficient salt absorption may cause putrefactive fermentations.

It is therefore important to understand what may be achievable with the use of glycerol in heavy pig nutrition, not only from the point of view of *in vivo* and slaughtering performances, but also for its effect on meat and fat quality. To understand the effect of glycerol *per se* this trial used pure glycerol as crude glycerine is not a standard product.

2. Material and methods

2.1. Diets and animals

The study involved 80 Italian Duroc × Italian Large White pigs (average initial BW 42.6 ± 3.37), half barrows and half gilts subdivided in five groups of four replicates (four pigs per pen) according to litter, gender, live weight and age. Pigs received either a maize-based (55%) diet without glycerol (control), or a substitution of 5% or 10% maize (on a dry matter basis) with 5% or 10% glycerol, respectively, throughout the entire growing and finishing phases (G+F5 and G+F10, respectively), or a substitution of 5 or 10% maize with 5% or 10% glycerol during the finishing phase (100 to 160 kg; FIN5 and FIN10, respectively).

The diets were formulated according to the live weight of pigs (Table 1). The Net Energy content of the diets was calculated according to Noblet (1994). The transition from 90 to 120 diet to the 120 to slaughter diet was not contemporary to the start of the finishing phase. All pigs were wet fed (water to feed ratio of 2:1) and the daily ration was supplied in two meals all days except on Sunday when the pigs received only the morning meal. Glycerol (bidistilled glycerine 30 BE′) was added to water immediately before the meal for each pen. All pigs had free access to water. At the start of the trial, the feed ration was 1.8 kg/pig/day, which was increased by 0.2 kg weekly for two weeks and 0.1 kg weekly for eleven weeks up to 3.3 kg/pig/day, which was maintained until slaughter. Animals were weighed individually every 28 days, after 77 days (mean BW approximately 100 kg), and on the day before slaughter. Pigs were slaughtered when the mean BW reached

approximately 160 kg. Two replicates per group were slaughtered after 147 days of and two after 154 days.

Pigs were slaughtered according to industry-accepted procedures. Hot carcass weight, lean meat percentage by Fat–O–Meat'er instrument (Commission Decision 2001/468/CE), thighs, shoulder and loin weight were recorded during the first hour after slaughter. *Semimembranosus* and *biceps femoris* muscles pH[45′] was measured by pH-meter KNICK 910 (Portamess).

After the 24-h chilling period (0–2 °C) loins and thighs were weighed, and hams were trimmed to the typical Parma ham round-shape. Trimmed hams were weighed and final pH was measured on *semimembranosus* and *biceps femoris* muscles. The colour of the *semimembranosus* muscle was measured using a colorimeter Minolta Chroma-meter CR-300 (Illuminant D65, aperture size 8 mm) according to the CIE $L^*a^*b^*$ system (Poretta, 1993).

Subcutaneous fat and *gluteus medius* muscle were removed from ham trimmings to determine subcutaneous and intramuscular fat fatty acid composition and subcutaneous fat Iodine value. Samples were frozen in a conventional freezer and kept at −30 °C until analysis.

From eight loins for each group (two pigs selected randomly inside each pen × 2 gender × 1 replicate × 2 slaughtering day) were kept two portions. A 10–12 cm thick portion of loin (11th and 12th ribs) was subdivided into a sample used to measure drip loss (sample weight 80–100 g), a sample with thickness of 50 × 50 × 10 mm to measure cooking loss and tenderness as Warner–Bratzler shear force, and a sample (weight 200 g) to determine the proximate analysis of the *longissimus dorsi* muscle. A 30–35 cm thick portion of the same loins (2nd–3rd–4th and possibly 1st lumbar vertebrae) was used perform a visual panel test on raw meat and a sensory panel test on cooked meat.

Both hams of each pig were cured according to the production regulations of the Consorzio del Prosciutto di Parma (Consortium of Parma Ham) and weight losses were recorded after the 1st week of salting, at the end of the salting period and after nine months of curing.

2.2. Lipid analyses

The intramuscular fat was extracted by the chloroform/methanol method of Folch, Lees, and Sloane-Stanley (1957). Following De Pedro, Casillas, and Miranda (1997), the subcutaneous tissue was chopped into small pieces (approximately 0.5 cm³), placed in individual microwave-resistant glass containers, and heated in a laboratory microwave oven MDS-2000 (CEM CORPORATION Matthews North Carolina) of 650 W power and 2450 MHz microwave frequency for 10 min at 33% power. The liquid fat obtained was filtered through anhydrous sodium sulphate. These samples were used for both fatty acid composition analysis and Iodine value. The preparation of methyl esters for both intramuscular and subcutaneous fat was performed following the method proposed by Stoffel, Chu, and Ahrens (1959). About 100 mg of fat was dissolved in methanolic HCl (5 ml) and placed at 100 °C for 40 min. After cooling, 2 ml of water and 2 ml of hexane were added. The organic phase was filtered through anhydrous sodium sulphate and injected into a Trace Ultra gas chromatograph (Thermo Electron Corporation) equipped with a flame ionization detector and an automatic injection system (S 2000 Thermo Electron Corporation). The column was a SP 2380 fused-silica capillary column (30 m length, 0.25 mm i.d. 0.20 μm film thickness). The initial column temperature was 160 °C raised to 250 °C in 20 min. The injector and detector temperature was 250 °C.

The helium carrier gas pressure was 70 kPa, and 1 μl of sample solution was injected (split ratio 1:40). Chrom–Card for Trace software for Windows (Version 2.3, Thermo Electron Corporation) was used for data analysis. Identification was accomplished by

Table 1
Composition of diets fed to control group

Periods	50–90 kg	90–120 kg	120 to slaughter
Ingredients (%)			
Maize meal	55.00	55.00	55.00
Barley meal	17.35	18.92	20.44
Soybean oil meal	14.50	13.00	11.50
Soft wheat bran	10.00	10.00	10.00
Calcium carbonate	1.20	1.20	1.20
Dicalcium phosphate	0.80	0.80	0.80
Sodium chloride	0.40	0.40	0.40
Mineral-vit. premix	0.50	0.50	0.50
L-Lysine HCl	0.20	0.18	0.16
DL-Methionine	0.05	0.00	0.00
Calculated values			
Net energy (Mcal/kg)	2.29	2.29	2.30
Lysine (%)	0.80	0.75	0.70
Lysine:N.E. ratio (g/Mcal)	3.50	3.28	3.06

comparing the retention time of the unknown fatty acid methyl esters (FAME) with those of known FAME standard mixtures (Supelco, Inc. Alltech Associated, Inc., Deerfield, IL).

Iodine value was determined using the Hanus method (AOAC 920.158, Fats and Oils Hanus Method, 1990).

2.3. Longissimus dorsi muscle analyses

Drip loss and cooking loss were determined by Honikel's gravimetric methods (Honikel, 1998).

For drip loss, a meat sample of approximately 80–100 g (±0.05 g) was placed within a plastic box on a supporting mesh ensuring that the sample did not make contact with the box and sealed. After 24 h at a chill temperature (1–5 °C) the samples were taken out from the box, dabbed lightly on filter paper and weighed again.

Drip loss was expressed as a percentage of the initial weight. For cooking loss, a freshly cut meat sample of thickness 50 × 50 × 10 mm was weighed (weight 1) and placed in a water-bath, with the water boiling continuously, in a thin plastic bag with its opening above the surface. All the samples were cooked in the same water-bath at the same time at 80 °C for 60 min to ensure a core temperature of at least 75 °C. After they had been removed from the water-bath, the samples were cooled under tap water for 20 min and kept at room temperature until equilibrated. The meat was then taken from the bag, dabbed lightly on filter paper and weighed (weight 2). The cooking loss was expressed as a percentage of the initial sample weight according to the following equation: cooking loss = $100 \times ((\text{weight } 1 - \text{weight } 2)/\text{weight } 1)$.

Warner–Bratzler shear force (WBSF) was determined by AMSA methods (AMSA, 1995). Cooked meat samples were cooled for 24 h at 4 °C. Six round cores (1.27 cm diameter) were removed from each sample parallel to the long axis of the muscle fibers by a mechanical coring device. Each core was sheared once through the center by a WBSF device (V-shape blade) connected to an Instron Universal Testing Machine (model 1011, Instron Corp., Canton, MA). A 50-kg compression load cell and 200 mm/min crosshead speed were used. WBSF was expressed as peak force (kg). The six cores were averaged for statistical analysis.

The proximate chemical composition of the muscle tissues was determined according to standard methods of AOAC (1990) on freeze-dried milled samples. The measurement of intramuscular fat content was determined by the Soxhlet method (Soxtec System HT6, Tecator AB). Crude protein was determined using a Kjeldahl Nitrogen/Protein Analyzer. (Gerhadt Vapodest 50, Gerhardt. GMBH). Ash content was determined by ashing samples in a muffle furnace at 500 °C.

2.4. Longissimus dorsi muscle sensory evaluation

The longissimus dorsi muscle was removed from the bone (Schivazappa, Virgili, & Puglia, 2001) and divided into chops with a thickness of about 1.5 cm and immediately placed in vacuum at −20 °C until analysis, within one month. The sensory tests were conducted following the standard UNI 10957 (UNI – Norma italiana, Ente Nazionale Italiano di Unificazione, 2003). A panel of nine assessors were selected and trained according to the ISO 8586-1 (International Organization for Standardization, 1993) and 8586-2 (International Organization for Standardization, 1994) rules. A descriptive form was used for the sensory evaluation setting out nine sensory attributes (two visual, one olfactory, two flavour-related and four tactile). The descriptive factors analyzed were colour and marbling for raw samples and odour intensity, flavour intensity, buttery flavour, tenderness, juiciness, masticability, fibrous texture for cooked meat. These factors were evaluated with the use of a

structured continuous scale of values between 0 and 10 (0 = absence of sensation, 10 = greatest intensity of sensation). The scales (0–10) were as follows. Color: 0–2, light pink, reference samples chicken breast (t 0–8 °C); 2–4, dark pink, reference samples pork chop (t 0–8 °C); 4–5, light red, reference samples pork chop after 2 h at room temperature; 5–6, bright red, reference samples beef steak (t 0–8 °C); 7–8, dark red, reference samples neck after few days; 9–10, brown, reference samples horse steak after few days. Marbling: 0–2, low on one side of the slice; 2–3, high on one side of the slice; 4–5, low on two or three side of the slice; 6–7, high on two or three side of the slice; 7–8, low on all sides of the slice; 9–10, high on all sides of the slice. Masticability (number of chewings required to masticate the sample for swallowing): 0–2, more than 30 bites (min. 27); 2–4, from 27 to 21 bites; 4–6, from 21 to 15 bites; 6–8, from 15 to 9 bites; 8–10, from 9 to less than 5 bites. Fibrous texture (perception of the muscle fibers in the sample after 3–4 chewings): 0–2, not all fibrous; 2–4, not much fibrous; 4–6, quite fibrous; 6–8, fibrous; 8–10, very fibrous. The day before the sensory assessment, the vacuum samples were thawed at 2–8 °C. For raw evaluations, samples were removed from vacuum about 1-h before the test and stored at 2–8 °C until analysis. Colour and marbling were always evaluated on a whole chop placed on an opaque white polystyrene commercial container for food (Parolari, 1985).

The evaluation of the cooked meat was on two small cubes (1.5 × 1.5 × 1.5 cm), eliminating connecting parts that might differentiate them. Cooking was performed on a cast iron hot plate brought to about 200 °C at least half an hour prior to the test. The temperature of the meat was monitored constantly with a probe. The chops were turned every 2 min and removed from the hot plate once their core temperature reached 70 °C. They were then cut into homogeneous cubes immediately and served hot (Schivazappa et al., 2001).

Each individual test involved the evaluation of all five groups, first evaluating the raw meat and then the cooked samples. The order of presentation of the different samples over the five testings was varied during the test to avoid possible effects in the response of the assessors based on order of presentation/cooking. All samples were coded with three-figure numbers, changing for each tasting session.

2.5. Statistical analysis

The data regarding body weight gain and food conversion rate were subjected to variance analysis with GLM procedure using the SAS System, 8.2 release for Windows, according to the following model: $y_{ij} = M + D_i + E_{ij}$ where y_{ij} = dependent variable observed on the jth subject (the pen) of the ith subgroup; M = general mean; D_i = diet (i = 1, 5); E_{ij} = residual error. There were four pens, two pens with castrated males and two pens with entire females, for each of five dietary treatments. The Bonferroni t test (α = 0.01, 0.05) was used for pair-wise comparisons of variables differing by $P \leqslant 0.05$. The model used for the other measured parameters (except the sensory panel test) was: $y_{ijkl} = M + D_i + G_j + S_k + (DGS)_{ijk} + E_{ijkl}$ where y_{ijkl} = dependent variable observed on the lth subject (the pig) of the ijkth subgroup; M = general mean; D_i = diet (i = 1,5); G_j = slaughtering day (j = 1, 2); S_k = sex (k = 1, 2); $(DGS)_{ijk}$ = interaction diet × slaughtering day × sex; E_{ijkl} = residual error. The Bonferroni t test (α = 0.01, 0.05) was used for pair-wise comparisons of variables differing by $P \leqslant 0.05$.

The sensory panel test analysis of the data was carried out in accordance with the UNI 10957 regulations. The data as a whole was subjected to univaried variance analysis with three factors (samples, assessors and replicate) and two interactions (three-way ANOVA) to study the effects linked to the product, the replicate/assessment and the assessors (SPSS vers.15.0 – univaried GLM) by statistical testing of multiple comparison on the basis of

Table 2
Growth performance data for heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods

Feeding period	Control	Glycerol 5 Growing-finishing	Glycerol 10 Growing-finishing	Glycerol 5 Finishing	Glycerol 10 Finishing	Error mean square
Pens (n)	4	4	4	4	4	
Mean live weight						
Day 0 (kg)	42.6	42.6	42.6	42.5	42.6	9.15
After growing period (kg)	101.7	102.4	100.3	101.5	102.0	7.83
At slaughtering (kg)	161.1[ab]	161.8[a]	156.1[b]	159.6[ab]	156.1[b]	3.76
Average daily gain						
Growing period (g/d)	767	777	749	767	772	1209.41
Finishing period (g/d)	814[a]	814[a]	764[ab]	794[a]	742[b]	3176.35
Growing and finishing (g/d)	790[a]	795[a]	756[a]	780[ab]	757[b]	1108.76
Feed:gain ratio (on DM)						
Growing period	2.41[xy]	2.38[y]	2.47[x]	2.41[xy]	2.40[xy]	0.0012
Finishing period	3.28[c]	3.30[c]	3.49[ab]	3.37[bc]	3.56[a]	0.0036
Growing and finishing	2.84[c]	2.84[c]	2.97[a]	2.89[bc]	2.95[ab]	0.0008

[abc] Different letters, within a row, indicate significant differences ($P \leqslant 0.01$).
[xyz] Different letters, within a row, indicate significant differences ($P \leqslant 0.05$).

Table 3
Hot carcass weights and wholesale cut weights from heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods

Feeding period	Control	Glycerol 5 Growing-finishing	Glycerol 10 Growing-finishing	Glycerol 5 Finishing	Glycerol 10 Finishing	Error mean square
Animals (n)	16	16	16	15	16	
Hot carcass weight[a] (kg)	135.8	135.9	131.4	134.3	131.0	61.87
Dressing percentage (%)	84.3	84.0	84.2	84.2	83.9	1.09
Lean meat percentage (%)	48.1	49.4	49.3	48.6	49.1	5.50
Ham weights (kg)	34.0	34.3	33.0	33.4	32.8	6.52
Ham yield[b] (%)	25.0	25.2	25.1	24.9	25.0	1.05
Shoulder weights (kg)	19.5	19.1	18.8	19.1	18.6	1.67
Shoulder yield[b] (%)	14.4	14.0	14.3	14.2	14.2	0.22
Loins "Bologna cut" weight (kg)	15.2	15.3	14.6	14.9	14.6	1.23
Loin yield[b] (%)	11.2	11.3	11.1	11.2	11.0	0.34

[a] Diaphragm, kidneys and flare fat.
[b] Hot carcass weight.

Table 4
Ham muscle quality characteristics from heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods

Feeding period	Control	Glycerol 5 Growing-finishing	Glycerol 10 Growing-finishing	Glycerol 5 Finishing	Glycerol 10 Finishing	Error mean square
Animals (n)	16	16	16	15	16	
45 min pH						
Semimembranosus	6.06	5.99	6.04	6.01	6.02	0.0787
Biceps Femoris	6.04	6.06	6.08	6.12	6.19	0.0635
24 h pH						
Semimembranosus	5.61	5.61	5.62	5.57	5.56	0.0051
Biceps Femoris	5.66	5.64	5.67	5.65	5.61	0.0098
Semimembranosus color						
Lightness (L^*)	49.25	47.95	49.61	48.50	50.01	8.2869
Redness (a^*)	9.59	9.93	9.54	10.82	10.13	3.0686
Yellowness (b^*)	4.58	4.30	4.67	4.96	4.97	1.2277
Chroma	10.67	10.84	10.65	1.93	11.31	3.7763
Hue angle	25.25	23.25	26.00	4.58	25.94	14.8884
Cold hams weight (kg)	33.5	33.8	32.5	33.0	32.3	6.37
Cooling loss (%)	1.4	1.4	1.4	1.4	1.4	0.01
Trimmed hams weight (kg)	27.7	28.0	27.1	27.1	26.7	4.38
Trimming loss (%)	17.2	17.3	16.8	17.7	17.4	1.83
Hams weight after one week salting (kg)	27.1	27.4	26.5	26.6	26.1	4.19
Weight loss after one week salting (%)	2.1	2.1	2.1	2.1	2.1	0.10
Hams weight after salting (kg)	26.6	26.9	26.0	26.1	25.6	4.04
Weight loss after salting (%)	4.0	4.0	4.0	3.9	3.9	0.31
Hams weight after 9 m curing (kg)	20.0	20.2	19.6	19.6	19.3	2.57
Weight loss after 9 m curing (%)	28.0	27.8	27.7	27.6	27.8	2.36

calculation of least significance difference (LSD) to identify difference sub-groups; a spider plot graphic was generated by excel.

3. Results and discussion

3.1. Rearing and slaughtering

Group G+F5 (5% pure glycerol both in growing and in finishing period) showed the same rearing performances (Table 2) as the control. Group G+F10 showed poorer ($P \leqslant 0.01$) growth performances than controls, and therefore, a worse feed:gain ratio ($P \leqslant 0.01$). In the same way, groups FIN5 and FIN10 showed similar growth performance as controls in the growing period; whereas, in the finishing period group FIN5 showed similar performance, and group FIN10 had a poorer ($P \leqslant 0.01$) growth rate and feed:gain ratio than controls.

The inferior performance of pigs receiving the 10% glycerol diets may be due to free glycerol excretion via the urine. Serum glycerol is transported across cell membranes very quickly through the aquaglyceroporins (Jensen, 2002; Kozono, Yasui, King, & Agre, 2002) by osmotic or concentration gradients. In the cytoplasm

Table 5
Loin quality characteristics from heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods

Feeding period	Control	Glycerol 5 Growing-finishing	Glycerol 10 Growing-finishing	Glycerol 5 Finishing	Glycerol 10 Finishing	Error mean square
Animals (n)	16	16	16	15	16	
Cold loin weight (kg)	15.0	15.1	14.4	14.7	14.4	1.19
Cooling loss (%)	1.28	1.34	1.32	1.27	1.26	0.0163
Loins (n)	8	8	8	8	8	
Drip loss (%)	1.56	1.89	1.57	1.95	2.27	0.6125
Cooking loss (%)	39.1[xy]	39.2[xy]	38.8[y]	39.7[xy]	40.9[x]	1.93
Warner Bratzler shear force (kg)	3.12	3.18	3.33	3.34	3.15	0.1669
Proximate analysis[a]						
Crude protein (%)	86.96	85.90	85.80	84.77	86.16	12.8717
Ether extract (%)	8.82	9.46	10.01	10.48	9.78	7.5839
Ash (%)	4.22	4.18	4.26	4.17	4.29	0.0228

[a] Dry matter.
[xyz] Different letters, within a row, indicate significant differences ($P \leqslant 0.05$).

Table 6
Fatty acid composition of ham subcutaneous fat from heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods

Feeding period		Control	Glycerol 5 Growing-finishing	Glycerol 10 Growing-finishing	Glycerol 5 Finishing	Glycerol 10 Finishing	Error mean square
Fatty acids							
Myristic (%)	(C14:0)	1.13	1.15	1.07	1.10	1.19	0.0262
Palmitic (%)	(C16:0)	22.62	22.25	21.83	22.61	23.27	1.6144
Palmitoleic (%)	(C16:1)	1.60	1.62	1.57	1.64	1.76	0.0786
Stearic (%)	(C18:0)	14.85	14.32	14.47	14.66	14.51	1.0848
Octadecenoic (%)	(C18:1n9 +C18:1n7)	44.47[b]	45.66[ab]	46.29[a]	45.26[ab]	45.02[ab]	1.5227
Linoleic (%)	(C18:2)	13.65	13.24	12.91	12.97	12.6	1.6667
Linolenic (%)	(C18:3)	0.22	0.23	0.22	0.23	0.21	0.0016
Eicosenoic (%)	(C20:1)	0.81	0.89	0.99	0.91	0.85	0.0230
Eicosadienoic (%)	(C20:2)	0.64	0.64	0.65	0.62	0.59	0.0034
Iodine value		65.2	65.9	66.1	64.5	64.2	4.67
Saturated (%)		38.61	37.72	37.37	38.38	38.97	2.6674
Monounsaturated (%)		46.88[b]	48.18[ab]	48.85[a]	47.82[ab]	47.63[ab]	12.5673
Polyunsaturated (%)		14.52	14.10	13.78	13.81	13.40	1.7701

[abc] Different letters, within a row, indicate significant differences ($P \leqslant 0.01$).

Table 7
Fatty acid composition of intramuscular fat from *gluteus medius* of heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods

Feeding period		Control	Glycerol 5 Growing-finishing	Glycerol 10 Growing-finishing	Glycerol 5 Finishing	Glycerol 10 Finishing	Error mean square
Fatty acids							
Myristic (%)	(C14:0)	1.19	1.15	1.10	1.21	1.18	0.0183
Palmitic (%)	(C16:0)	23.71	23.24	23.17	23.68	23.41	0.8502
Palmitoleic (%)	(C16:1)	2.83	2.73	2.68	2.95	2.95	0.2584
Stearic (%)	(C18:0)	13.38	12.92	13.09	13.23	13.17	1.0480
Octadecenoic (%)	(C18:1n9 +C18:1n7)	46.45	45.39	47.60	47.00	46.82	7.7467
Linoleic (%)	(C18:2)	9.68	11.15	9.44	9.22	9.56	4.1405
Linolenic (%)	(C18:3)	0.19	0.20	0.19	0.19	0.20	0.0019
Eicosenoic	(C20:1)	0.52	0.54	0.60	0.56	0.56	0.0081
Arachidonic (%)	(C20:4)	2.04	2.69	2.12	1.96	2.15	0.6010
Saturated (%)		38.28	37.30	37.36	38.12	37.75	2.4712
Monounsaturated (%)		49.81	48.66	50.89	50.51	50.34	9.2482
Polyunsaturated (%)		11.91	14.04	11.75	11.36	11.90	7.6222

glycerol is activated by glycerol-kinase to glycerol-3-phosphate, which cannot be transported through aquaglyceroporins. Therefore, the amount of glycerol that cells can retain depends on the enzymatic glycerol-kinase activity which differs according to cell type (Coppack, Persson, Judd, & Miles, 1999) and animal species. Doppenberg and Van der Aar (2007) found that increasing the glycerol dose from 5% to 15% resulted in a more dramatic decrease in metabolisable energy in pigs than in layers or broilers. According to Bartelt and Schneider (2002), the glycerol Metabolizable Energy (ME) for pigs fed 5%, 10% and 15% represents 97%, 80% and 59% of the Gross Energy, respectively.

Lammers et al. (2007), in trials on weaning piglets kept in metabolic cages, found an ME of 3601, 3329 and 2579 kcal/kg using doses of 5%, 10% and 20%, respectively. In finishing pigs they found that energy in urine doubled with the increase of dietary glycerol from 10% to 20%.

Kijora and Kupsch (1996) fed growing/finishing pigs (semi ad libitum, i.e. the 80% of the ad libitum intake) a diet containing the 0%, 5% or 10% of pure or crude glycerol and found an increase of feed intake in diets with glycerol in conjunction with a greater weight gain. Subsequently, feed:gain ratio was similar for all groups. In a subsequent trial, Kijora et al. (1997) found similar results in relation to feed intake and growth rate, but a tendency towards a poorer feed: gain ratio for pigs fed 10% glycerol.

No differences were seen among groups (Table 3) for dressing yield, lean meat content and lean cuts (thigh, loin, shoulder) weight and yield. Similar results were obtained by Mourot et al. (1993) who found no significant differences due to glycerol on carcass lean meat content and lean cut weights. Kijora and Kupsch (1996) found that pigs fed the 10% crude glycerol had leaner carcasses than controls, but the authors ascribed the differences to different gain intensity in the fattening period and not to glycerol intake.

3.2. Meat and fat quality

Different diets did not influence the pH and colour of thigh muscles (Table 4) or the ham weight loss recorded over 9 months of curing, the period when the majority of weight loss occurs.

The "Bologna cut" loin cooling loss did not differ among groups (Table 5). Neither drip loss nor cooking loss was influenced by glycerol, even though there appeared to be a tendency toward higher loss in glycerol-fed pigs. These results are in contrast to the results of Mourot et al. (1994), who found a significant reduction of drip and cooking loss in pigs fed 5% glycerol, and Cerneau et al. (1994), who found an increased cooking yield of the ham. Kijora

Table 8
Mean scores for sensory attributes of loins from heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods

Feeding period	Control	Glycerol 5 Growing-finishing	Glycerol 10 Growing-finishing	Glycerol 5 Finishing	Glycerol 10 Finishing	Error mean square
Colour	4.3[b]	4.3[b]	4.2[b]	5.0[a]	4.2[b]	0.96
Marbling	7.1[c]	6.6[d]	8.0[a]	7.6[b]	7.6[b]	1.13
Odour-intensity	5.2	5.3	5.4	5.4	5.1	1.02
Flavour intensity	5.1	5.0	5.1	5.1	5.1	0.99
Butter flavour	2.6[ab]	2.4[b]	2.8[a]	2.8[a]	2.8[a]	0.89
Tenderness	6.0[x]	5.7[x]	5.8[x]	5.3[y]	5.7[x]	1.14
Juiciness	4.8	5.0	5.1	4.6	4.6	1.29
Masticability	5.8	5.8	6.0	5.6	6.0	1.08
Fibrous texture	4.3	4.2	4.3	4.7	4.3	1.39

[abc] Different letters, within a row, indicate significant differences ($P \leqslant 0.01$).
[xyz] Different letters, within a row, indicate significant differences ($P \leqslant 0.05$).

Average loin sensory profile

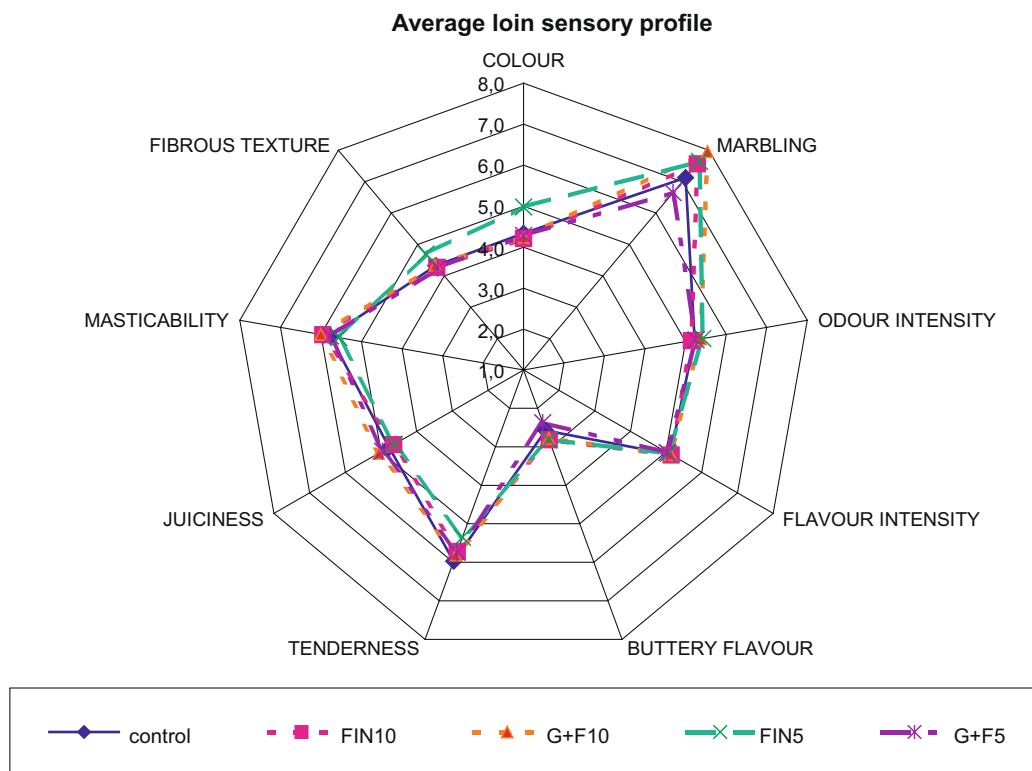control · FIN10 · G+F10 · FIN5 · G+F5

Fig. 1. Spider's web graph of the sensory profiles of loins from heavy pigs fed 0%, 5%, or 10% glycerol during the finishing period or during the growing and finishing periods.

and Kupsch (1996) found a tendency towards a reduction of drip and press water loss in loin chops.

The fatty acid composition of the ham subcutaneous fat (Table 6) was influenced by treatment. Pigs receiving the higher dose of glycerol for the entire growing-finishing period showed a higher ($P \leqslant 0.01$) octadecenoic acid content than controls and a tendency toward a reduction in palmitic, stearic and linoleic acids. Because of the tendency toward a reduction of both saturated and polyunsaturated fatty acid, Iodine value did not differ between group G+F10 and control. The subcutaneous fatty acid composition of other groups was intermediate. Mourot et al. (1994) also found an increase in oleic acid with a significant reduction in linoleic acid. Cerneau et al. (1994) found an increase in palmitic acid and a decrease in linoleic acid. Kijora et al. (1997) found a significant reduction in linoleic acid.

Intramuscular fatty acid composition (Table 7) was not influenced by the dietary treatment.

Thus in heavy pigs, the effect of substitution of 5% or 10% of maize meal with pure glycerol did not affect the fresh meat quality significantly and the suitability of ham for parma ham production. Differences found between our results and those in the literature may be due to genetic differences in the pigs concerned but are mostly attributable to different slaughtering age and weight. In fact, the pigs of Mourot et al. (1994), Cerneau et al. (1994) and Kijora et al. (1997) were slaughtered at approximately 5–6 months of age at a live weight of 99–112 kg; whereas the pigs in the present trial were slaughtered at nine months at a live weight of 160 kg. A very important result is that the weight loss of hams during curing was not influenced by diet. Increased weight loss is attributable to increased water losses resulting in meat which is too salty and tough; whereas decrease in weight loss is detrimental because insufficient water loss, particularly in the salting period, may facilitate microbial decay fermentations. Pure glycerol did not substantially modify the fatty acid composition of subcutaneous fat achievable with traditional diets.

3.3. Sensory attributes

The attribute scores for sensory analysis (Table 8), showed significant differences for four sensory attributes (colour and marbling ($P \leqslant 0.001$), buttery flavour ($P \leqslant 0.01$) and tenderness ($P \leqslant 0.05$)). The G+F10, FIN5 and FIN10 groups showed higher marbling values and higher butter flavour values than the G+F5 group; the control group showed intermediary values for both attributes. The FIN5 group showed colour and tenderness values different from the other groups. However the numeric differences between groups were small when subjected to scale expansion (0–10) as shown by Spider's web graph (Fig. 1). Thus there were not enough consistent differences in these attributes to drawn any conclusion about the effects of feeding glycerol on sensory characteristics.

4. Conclusions

The substitution of 5% of maize meal with pure glycerol did not modify the in vivo and slaughtering performance of heavy pigs or the suitability of the meat and fat for curing, whereas a substitution of 10% caused a worsening of growth and feed efficiency performance without jeopardizing the suitability of meat and fat for curing. So far as the sensory characteristics were concerned, the tests on the longissimus dorsi muscle were not unequivocal. More research is needed because the sensory evaluation of meat destined for fresh consumption may help improve heavy pig value.

The future increasing production of biodiesel will provide crude glycerine that could be price competitive with cereals, mainly maize. More information is thus needed about the use of crude glycerine for a high quality production, such as heavy pig production.

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