

Article

Growth Performance, Carcass and Pork Quality Traits of Growing-Finishing Pigs with High and Low Breeding Values for Residual Feed Intake Fed Diets with Macauba (*Acrocomia aculeata*) Pulp as Alternative Raw Material

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Abstract: This study evaluated the effects of dietary macauba pulp on the growth performance, carcass, and pork traits of growing-finishing pigs; and whether differences in residual feed intake breeding values could influence the pigs' growth responses to macauba pulp inclusion in the diet. A total of 282 (34.8 ± 4.40 kg) pigs (barrows and females), progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake, were pair-housed on the basis of sex, breeding value, and initial BW. Diets with (macauba) or without (control) of 50 g/kg of macauba pulp inclusion were randomly assigned to the experimental pens. There were eight treatment groups: HRFI barrows were fed the control diet; HRFI barrows were fed the macauba diet; LRFI barrows were fed the control diet; LRFI barrows were fed the macauba diet; HRFI female pigs were fed the control diet; HRFI female pigs were fed the macauba diet; LRFI female pigs were fed the control diet; and LRFI female pigs were fed the macauba diet. The trial lasted 90 days and was divided into four phases: growing phase 1 (G1) and 2 (G2); and finishing phases 1 (F1) and 2 (F2). There was no interaction between sex, breeding value, and diet for performance, carcass, and pork traits. Barrows had higher feed intake (ADFI), daily gain (ADG), feed conversion rate (FCR), and final body weight than female pigs. The breeding value had no effect on performance measurements. The inclusion of macauba pulp in the pigs' diets did not affect any growth parameter during G1, G2 and F1 phases. However, reduced ADFI and improved FCR were observed in F2. Female pigs had lower backfat thickness (BF) and higher loin eye area (LEA) than barrows. HRFI pigs had higher hot carcass weight and LEA, and lower BF than LRFI pigs. There was no effect of macauba pulp inclusion on carcass traits. Pork from barrows presented lower Warner–Bratzler shear force and higher fat content than pork from the females. There was no effect of breeding value on pork traits. Pork from pigs fed the macauba diet showed lower moisture content and water-holding capacity. In conclusion, macauba pulp can partially replace corn without reducing the performance of pigs. Regardless of sex and breeding value for RFI, pigs responded similarly to macauba pulp inclusion in diets.

Keywords: swine; biofuels coproducts; feed efficiency; palm; alternative feedstuff

1. Introduction

Approximately three-quarters of swine production costs are related to feed [1]. The food-feed-fuel conflict has increased the demand and prices of traditional feedstuffs, affecting the profitability of livestock production [2,3]. Reducing commodities dependence

(e.g., corn and soybean) by introducing alternative ingredients, such as biofuels industry co-products, is vital to economically and environmentally improve pig production systems [4].

Economic, environmental, and geopolitical concerns over fossil-fuel dependency have intensified the focus on developing renewable energy sources. In this context, due to its large production (4000 L of oil per hectare per year) and high-quality oil ($\pm 73\%$ unsaturated fatty acids), Macauba (*Acrocomia aculeata*) has emerged as a raw material for biodiesel production in Brazil [5,6]. After macauba fruit oil extraction, co-products, such as pulp and kernel cakes, are produced and have been indicated as an economically viable alternative in pig feed.

As an omnivore species, pigs are ideal for converting non-human-edible co-products into high-quality food animal protein [2]. Dias et al. [7] reported that up to 100 g/kg of macauba pulp inclusion did not affect growth performance and body composition in growing pigs. In addition, Costa Júnior et al. [8] found that up to 103 g/kg of macauba pulp inclusion improved lean meat deposition without affecting the performance of finishing pigs.

Not only the inclusion of alternative ingredients but also the improvement of the feed efficiency of pigs can contribute to improving the profitability and sustainability of the system. In general, feed efficiency is expressed as the feed conversion ratio (FCR), that is, the ratio between feed intake and weight gain [9]. In turn, selecting pigs with higher growth rates and lower fat deposition can reduce FCR [9]. However, as FCR is a ratio trait, its selection responses can be erroneous [10].

For a more accurate individual comparison of animals, Koch et al. [11] proposed an adjustment of feed intake according to weight gain and average body weight, known as residual feed intake (RFI). Traditionally, RFI is a moderately heritable trait, genetically correlated with rate of gain and backfat thickness [12]. Therefore, it is evaluated as the difference between the feed intake observed and the feed intake expected based on backfat and growth rate [9]. The higher the RFI value, the lower the feed efficiency of the animal [13].

Nevertheless, including alternative feedstuff in commercial farms may alter the predicted performance of current commercial genotypes once pig improvement programs are carried out with pigs fed traditional cereal-based diets [14,15]. Therefore, the objective of this study was to evaluate the effects of dietary macauba pulp on the growth performance, carcass traits, and pork traits of growing-finishing pigs (30–150 kg BW); and whether differences in residual feed intake breeding values could influence pig growth responses to macauba pulp inclusion in the diet.

2. Materials and Methods

2.1. Ethic Statement

The Institutional Ethics Commission on the Use of Farm Animals of the Universidade Federal de Viçosa, MG, Brazil approved all the procedures performed in this experiment (protocol 83/2019).

2.2. Animals, Experimental Design, and Diets

Two hundred and eighty-two pigs (barrows and females) progeny of sires (Topigs-Norvisn) with high or low breeding value for residual feed intake (RFI) crossed with Topigs-Norvisn sows were randomly selected at 34.7 ± 4.40 kg BW and 76 ± 3 days old, distributed into eight groups, and pair-housed in slatted concrete floor pens (2.41×1.36 m). They had free access to feed by a semi-automatic feeder and water via a nipple drinker (Pig Breeding Research Facility of the Universidade Federal de Viçosa, MG, Brazil). The study was carried out in two batches. Batch 1 consisted of 134 pigs (72 barrows and 62 females) with 33.4 ± 3.4 kg of initial BW and 73 ± 2 days old, and batch 2 consisted of 148 pigs (78 barrows and 70 females) with 35.98 ± 4.9 of initial BW and 79 ± 2 days old. It was performed as a $2 \times 2 \times 2$ factorial design in which pigs were pair-housed in experimental

pens based on sex (barrows and females), breeding value (progeny of boars with high and low RFI), and initial BW and the diets (without and with 50 g/kg of macauba pulp inclusion) were randomly assigned to them. Therefore, there were eight treatment groups: treatment 1 consisted of high residual feed intake (HRFI) barrows fed the control diet ($n = 21$); treatment 2 consisted of HRFI barrows fed the macauba diet ($n = 21$); treatment 3 consisted of low residual feed intake (LRFI) barrows fed the control diet ($n = 16$); treatment 4 consisted of LRFI barrows fed the macauba diet ($n = 17$); treatment 5 consisted of HRFI female pigs eating the control diet ($n = 18$); treatment 6 consisted of HRFI female pigs eating the macauba diet ($n = 18$); treatment 7 consisted of LRFI female pigs eating the control diet ($n = 14$); and treatment 8 consisted of LRFI female pigs eating the macauba diet ($n = 16$). The experimental period lasted 90 days (day 0 to 90) and was divided into four phases: growing phases 1 (0–20 days; G1) and 2 (21–40 days; G2); and finishing phases 1 (41–65 days; F1) and 2 (66–90 days; F2).

The macauba level was defined based on a previous study [7] which demonstrated that up to 50 g/kg of macauba pulp inclusion had no deleterious effects on the growth performance and carcass traits of growing pigs (30 to 65 kg BW). The experimental diets (Table 1) were formulated to meet or exceed the nutritional requirements of all nutrients according to Rostagno et al. [16] recommendations and to have similar levels of metabolizable energy between treatments in each growth phase.

Prior to the study, macauba pulp was analyzed for dry matter, crude protein and fiber, ash, phosphorus and calcium content (Table 2) [17]. Gross energy was assessed by an adiabatic bomb calorimeter (Parr Instrument Co., Moline, IL). Calcium and phosphorus content were measured by the ICP-OES method 2011.14 [18]. The nutritional composition of the raw materials was obtained from Rostagno et al. [16]. The metabolizable energy content of diets was calculated according to Sauvante et al. [19].

Table 1. Experimental diets ingredients and composition for the corn–soybean meal diets without (control) or with 50 g/kg of macauba pulp inclusion (macauba).

Ingredients	0–20 Days (G1)		21–40 Days (G2)		41–65 Days (F1)		66–90 Days (F2)	
	Control	Macauba	Control	Macauba	Control	Macauba	Control	Macauba
Corn, %	65.91	59.00	66.53	63.43	66.08	65.77	74.34	72.69
Macauba, %	0.00	5.00	0.00	5.00	0.00	5.00	0.00	5.00
Soybean oil, %	0.70	2.20	0.35	1.36	0.15	1.10	0.00	0.75
Soybean meal, %	30.50	30.90	31.00	28.00	32.00	26.35	24.00	19.90
Limestone, %	0.61	0.61	0.62	0.61	0.58	0.59	0.58	0.58
Dicalcium phosphate, %	1.40	1.40	0.84	0.84	0.56	0.56	0.46	0.46
NaCl, %	0.50	0.50	0.40	0.40	0.37	0.37	0.36	0.36
L-Lys HCl, %	0.09	0.09	0.00	0.10	0.00	0.00	0.00	0.00
DL-Methionine, %	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Vitamin-trace mineral premix ¹ , %	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
BHT, %	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Choline chloride, %	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Calculated content								
Metabolizable energy, kcal/kg *	3251	3251	3250	3250	3250	3250	3261	3250
CP, %	19.20	19.13	19.37	18.14	19.79	17.47	16.79	15.08
SID Lysine, %	1.076	1.071	1.021	1.010	1.048	0.889	0.843	0.724
Ca, %	19.20	19.13	19.37	18.14	19.79	17.47	16.79	15.08
Total P, %	0.64	0.66	0.53	0.52	0.45	0.45	0.41	0.41

¹ Mineral vitamin supplement (per kg of diet): Vit. A (5250 UI); Vit. D3 (750 UI); Vit. E (11 UI); Vit. K3 (1.5 mg); Vit. B1 (1 mg); Vit. B2 (2.4 mg); Vit. B6 (1 mg); Niacin (30 mg); Pantothenic acid (8.1 mg); Folic acid (0.53 mg); Biotin (0.05 mg); Vit. B12 (16.5 mcg); Copper (13.5 mg); Iodine (0.19 mg); Manganese (37.5 mg); Selenium (0.15 mg); Zinc (72 mg); Iron (72 mg); and Cobalt (0.19 mg). * Sauvante et al. [19].

Table 2. Macauba pulp composition.

Item	
Dry matter, %	94.17
Ash, %	5.02
Crude protein, %	4.74
Crude fiber, %	43.39
Ether extract, %	24.23
Phosphorus, %	0.05
Calcium, %	0.315
Gross energy, kcal/kg	3974
Metabolizable energy, kcal/kg *	2225

* Sauvante et al. [19].

Relative humidity and ambient temperature were registered hourly by data loggers (Klimalogg Pro, TFA Dostmann®Klima Logger Professional, model 30.3015, Wertheim, Germany). Lighting was not controlled.

2.3. Performance Measurements

Pigs were individually weighed at days 0, 21, 41, 66, and 90 without fasting. The feeding amount and leftovers were recorded daily (between 08:00 and 08:30 h). These values were used to calculate average daily feed intake (ADFI; g/d), average daily gain (ADG; g/d), and feed conversion rate (FCR; g/g).

2.4. Slaughter Procedure and Carcass Traits

All slaughtering procedures followed good animal welfare practices. At the end of the 90-day trial, one pig from each pen was subjected to 12 hours' fasting, weighed and slaughtered, following standard commercial proceedings. Hot carcass weight (HCW) of each pig was recorded to calculate the dressing percentage [20]. Carcasses were divided longitudinally, maintained at ambient temperature until approximately 45 min *postmortem* and then refrigerated at 4 °C for 24 h.

At 24 h *postmortem*, the left-half carcass was ribbed at the 10th rib region to assess backfat thickness (BF) and loin eye area (LEA). In short, BF was quantified by a digital caliper, and the muscle area of the *Longissimus dorsi* (LM) between the 10th and 11th cervical vertebra was covered with transparent paper and contoured using a permanent fine-tipped marker to determine LEA. The area within the outline was calculated by ImageJ software (version 1.51, National Institutes of Health, Bethesda, MD, USA).

At 15 min, 45 min, 1 h, 3 h, 6 h, 9 h, 12 h, and 24 h *postmortem*, the decline in pH and temperature was measured in the left LM of carcasses by a handheld pH/temperature measuring instrument (Testo SE & Co., Lenzkirch, FR, Germany). Bleeding was considered the baseline (minute 0) *postmortem*.

From the left-half carcass, a sample of 20 cm of LM (between the 10th cervical and the 1st lumbar vertebra) was collected for pork quality assessment. After 24 h of freezing at −20 °C, LM samples were divided into five chops (2.54 cm), individually vacuum packed and frozen for posterior analysis [21].

2.5. Pork Quality

Water-holding capacity (WHC) was evaluated in fresh LM by the centrifugal method [22]. Briefly, 5 g of meat samples free from fat and connective tissue were centrifuged at 3000 rpm for 10 minutes at 4 °C, and the liquid expelled was separated from the meat. WHC was expressed as the percent difference between weights measured prior to and after centrifuging. The average of two samples for each animal was considered.

Pork color was evaluated on the cranial surface of LM after 30 minutes of exposure to air by a portable spectrophotometer (HunterLab MiniScan EZ 45/0 LAV, Reston, VA, USA) adjusted to 31.8 mm port size, an illuminant D65 and a 10° angle to the observer. The L* (lightness), a* (redness), and b* (yellowness) values of each LM sample were defined

according to the CIELab scale as the mean of six spectrophotometer readings at six different points on the LM surface [23,24].

Cooking loss analysis followed the methodology described by Bruce et al. [25], with adjustments described by Silva et al. [26]. After a thawed period (16 h at 4 °C), vacuum-packaged chops were weighed and cooked at 71 °C for 40 min in a digital water bath with a stirrer (WEALAB). Then, the chops rested for 10 minutes in an ice bath to stop the cooking process. After this period, the chops were refrigerated for 16 h at 4 °C and weighed. Cooking loss was expressed as the percent difference between weights measured prior to and after cooking.

After cooking loss analysis, cooked samples were used in Warner–Bratzler shear force (WBSF) measurement, as proposed by [27]. From each chop, six cylindrical subsamples (1.27 cm diameter) were removed parallel to the longitudinal orientation of muscle fibers and free from fat and connective tissue. These cylindrical samples were sheared perpendicularly to the longitudinal orientation of the muscle fibers, in the Warner–Bratzler machine (GR Electrical Manufacturing Company, Manhattan, KS, USA). The maximum force to cut the cylindrical samples was recorded and the WBSF was determined by the average of six measures.

Sarcomere length was estimated by the laser diffraction technique [28]. Eight strands of the sheared cylindrical samples were removed and distinctly placed on a microscope slide. One drop of sucrose solution (0.2 M sucrose and 0.1 M NaHPO buffer at pH 7) at 4 °C was placed on each filament and a helium-neon laser (Model 05-LHR-021, MelleGriot, Carlsbad, CA, USA) was focused on those strands. The mean of eight diffraction bands was considered the sarcomere length according to the equation below:

$$\text{Sarcomere length } (\mu\text{m}) = \frac{0.6328 \times D \times \sqrt{\left(\frac{T}{D}\right)^2 + 1}}{T} \quad (1)$$

where, D = the distance (mm) between the lamina fixation support and the collection site of the diffuse laser bands (in this work, 120 mm were used) and T = distance (mm) between the extreme bands divided by 2.

Pork moisture, protein, fat, ash, and collagen were performed by near-infrared (NIR) spectroscopy analysis [17] on 120 g of the LM ground in a tissue homogenizer (TURRAX CT-132) after trimmed visible fat and connective tissues, using the FoodScan™ device (FoodScan, FOSS NIR systems Inc., Laurel, MD, USA).

2.6. Data Analysis

The experimental unit for performance analysis was the pen, while the slaughtered animal was the experimental unit for carcass and pork quality traits. Data were analyzed using the PROC GLM model of SAS (SAS®Version 9.4, SAS®Institute, Inc., Cary, NC, USA) licensed by Universidade Federal de Viçosa, considering the fixed effects of sex, breeding value, experimental diet, batch, and their interactions. For pH and temperature decline, the sampling time was introduced to the model and the comparisons were performed within each sampling time. A comparative analysis between means was performed by Tukey test. Statistical differences were considered significant at $p < 0.05$.

3. Results

Because of excessive wasted feed and health problems, data from seven experimental pens from batch 1; and three from batch 2 were not considered. The remaining animals stayed healthy and performed well. The first batch was conducted from January to April (summer) and the second one from June to September (winter). During batch 1, ambient temperature was 23.7 ± 3.6 °C and relative humidity was $82 \pm 14\%$. In batch 2, these values were 20.1 ± 2.3 °C and $69 \pm 6\%$, respectively.

3.1. Performance

No interaction between sex, breeding value, diet, and batch was observed for performance traits ($p > 0.05$; Table 3). On average, pigs started the trial at 34.7 ± 4.40 kg BW and 76 ± 3 days old and finished the trial at 133.7 ± 9.06 kg BW and 166 ± 3 days old. Whatever the sex, breeding value, and dietary treatment pigs had similar BW ($p > 0.05$) at the beginning of the trial.

Table 3. Effect of sex, sire breeding value, and diet on performance of pigs.

Phase/Traits	Sex		BV ¹		Diet		RMSE ³	<i>p</i> -Value		
	Barrows	Female	HRFI	LRFI	Control	Macauba ²		Sex	BV ¹	Diet
Experimental units	71	60	74	57	63	68				
0–20 days (G1)										
Initial body weight, kg	34.9	35.1	35.5	34.4	34.8	35.1	4.26	0.72	0.13	0.65
Average daily feed intake, g/day	2223	2045	2143	2125	2144	2124	190.5	<0.01	0.61	0.55
Average daily gain, g/day	1134	1061	1110	1085	1096	1100	98.0	<0.01	0.16	0.81
Feed conversion rate, g/g	1.96	1.94	1.94	1.97	1.96	1.94	0.169	0.46	0.33	0.43
Final body weight, kg	57.4	56.0	57.6	55.7	56.4	56.9	5.10	0.10	0.03	0.57
21–40 days (G2)										
Initial body weight, kg	57.4	56.0	57.6	55.7	56.4	56.9	5.10	0.10	0.03	0.57
Average daily feed intake, g/day	3012	2610	2847	2776	2819	2803	249.1	<0.01	0.11	0.71
Average daily gain, g/day	1156	1130	1120	1165	1148	1138	103.1	0.15	0.02	0.57
Feed conversion rate, g/g	2.61	2.33	2.55	2.39	2.47	2.47	0.240	<0.01	<0.01	0.98
Final body weight, kg	81.6	78.7	81.5	78.7	80.1	80.1	6.51	0.01	0.01	0.97
41–65 days (F1)										
Initial body weight, kg	81.6	78.7	81.5	78.7	80.1	80.1	6.51	0.01	0.01	0.97
Average daily feed intake, g/day	3334	2869	3113	3089	3096	3106	279.7	<0.01	0.63	0.85
Average daily gain, g/day	1164	1076	1124	1116	1106	1134	101.5	<0.01	0.64	0.12
Feed conversion rate, g/g	2.87	2.66	2.77	2.76	2.79	2.73	0.255	<0.01	0.95	0.17
Final body weight, kg	105.1	110.0	109.0	106.0	107.4	107.7	7.52	<0.01	0.02	0.79
66–90 days (F2)										
Initial body weight, kg	105.1	110.0	109.0	106.0	107.4	107.7	7.52	<0.01	0.02	0.79
Average daily feed intake, g/day	3675	3241	3401	3516	3528	3389	286.4	<0.01	0.03	0.01
Average daily gain, g/day	1148	1061	1095	1114	1102	1107	101.0	<0.01	0.31	0.82
Feed conversion rate, g/g	3.21	3.08	3.13	3.16	3.21	3.08	0.297	0.01	0.49	0.01
Final body weight, kg	137.6	129.4	134.5	132.5	133.3	133.7	7.84	<0.01	0.13	0.74
Entire fattening period (90 days)										
Initial body weight, kg	34.9	35.1	35.5	34.4	34.8	35.1	4.26	0.72	0.13	0.65
Average daily feed intake, g/day	3.144	2.734	2.983	2.925	2.997	2.920	221.2	<0.01	0.21	0.09
Average daily gain, g/day	1.157	1.067	1.124	1.106	1.118	1.114	62.3	<0.01	0.15	0.84
Feed conversion rate, g/g	2.72	2.57	2.65	2.64	2.68	2.62	0.183	<0.01	0.81	0.07
Final body weight, kg	137.6	129.4	134.5	132.5	133.3	133.7	7.84	<0.01	0.13	0.74

¹ Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake; ² Inclusion of 50 g/kg of macauba pulp in the diet; ³ Root Mean Square Error.

Regarding sex effects, barrows had greater ADFI ($p < 0.01$) and ADG ($p < 0.01$) than females, while FCR was similar between sexes ($p = 0.46$) in G1 phase. In G2 phase, barrows had higher ADFI ($p < 0.01$) and FCR ($p < 0.01$) than females whereas ADG did not differ between sexes ($p = 0.15$). In F1 and F2 phases barrows had greater ADFI ($p < 0.05$), ADG ($p < 0.05$), and FCR ($p < 0.05$) than females. Considering the entire fattening period, barrows had higher ADFI ($p < 0.01$), ADG ($p < 0.01$), and FCR ($p < 0.01$) than female pigs.

In respect of breeding value, it did not affect ($p > 0.05$) performance of pigs at the G1 phase. In the G2 phase, both genetic groups had similar ADFI ($p = 0.11$) but LRFI pigs had greater ADG ($p = 0.02$) and lower FCR ($p < 0.01$) than high HRFI pigs. No difference

was observed between LRFI and HRFI progeny pigs on performance traits in the F1 phase ($p > 0.05$). In F2 phase, LRFI progeny pigs had greater ADFI ($p = 0.03$) than HRFI pigs, while ADG ($p = 0.31$) and FCR ($p = 0.49$) were not affected by breeding value. Overall, the breeding value had no effect ($p > 0.05$) on performance measurements.

Concerning the diet effects, the inclusion of 50 g/kg of macauba pulp did not affect any performance trait in the first three experimental phases ($p > 0.05$). In F2 phase, animals receiving the macauba diet had lower ADFI ($p = 0.01$) and FCR ($p = 0.01$) while ADG did not differ from pigs fed control diet ($p = 0.82$). Overall, pigs fed control and macauba diets had similar ADFI ($p = 0.09$), ADG ($p = 0.84$), and FCR ($p = 0.07$).

3.2. Carcass Traits

No interaction between sex, breeding value, diet, and batch was observed for carcass traits ($p > 0.05$; Table 4). For sex effect, female pigs had lower slaughter body weight ($p < 0.01$), HCW ($p < 0.01$), BF ($p < 0.01$) and higher LEA ($p = 0.01$) than barrows. Regarding breeding value, HRFI pigs presented higher HCW ($p = 0.03$) and LEA ($p = 0.01$), and a lower BF ($p < 0.01$) compared to progeny from LRFI pigs. There was no effect ($p > 0.05$) of macauba pulp inclusion in the carcass traits.

Table 4. Effect of sex, sire breeding value, and diet on carcass traits of growing-finishing pigs.

Traits	Sex		BV ¹		Diet		RMSE ³	p-Value		
	Barrows	Female	HRFI	LRFI	Control	Macauba ²		Sex	BV ¹	Diet
Experimental units	71	60	74	57	63	68				
Slaughter body weight, kg	139.3	131.2	136.7	133.8	135.4	135.1	9.49	<0.01	0.09	0.90
Hot carcass weight, kg	119.6	112.4	117.5	114.5	116.2	115.8	8.03	<0.01	0.04	0.78
Dressing percentage, %	85.8	85.7	86.0	85.6	85.9	85.7	1.25	0.78	0.10	0.44
Backfat thickness, mm	22.2	16.2	17.7	20.7	18.8	19.6	4.35	<0.01	<0.01	0.27
Loin eye area, cm ²	53.9	56.8	57.2	53.6	56.1	54.6	6.78	0.01	<0.01	0.20

¹ Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake; ² Inclusion of 50 g/kg of Macauba pulp in the diet; ³ Root Mean Square Error.

3.3. Carcass pH and Temperature

No interaction between sex, diet, breeding value and batch was observed for the decline of pH and temperature of carcass at all sampling times ($p > 0.05$). Barrows had greater ($p < 0.05$) carcass pH from 45 min to 6 h after slaughter than female pigs (Figure 1A). Carcasses from HRFI pigs had greater pH ($p < 0.05$) at 12 h and 24 h *postmortem* than LRFI pigs (Figure 1B). Despite the similar response pattern, carcasses from barrows had higher ($p < 0.05$) temperatures at 9 h and 12 h after slaughter than female pigs (Figure 2A). There was no effect ($p > 0.05$) of breeding value (Figure 2B) on the temperature decline of carcasses. Macauba pulp inclusion did not affect the pH (Figure 1C) and temperature (Figure 2C) decline of carcasses at any time.

3.4. Pork Quality Traits

There was no interaction between sex, breeding value, diet, and batch for pork quality traits ($p > 0.05$; Table 5). Regarding sex, pork from barrows presented lower ash content ($p < 0.01$), WBSF ($p = 0.03$), and higher fat content ($p < 0.01$) compared with pork from the females. There was no effect of breeding value on the pork traits ($p > 0.05$). Concerning diet effect, pigs fed with 50 g/kg of macauba pulp had lower ($p < 0.01$) moisture and ash contents. Pigs fed the control diet showed higher WHC ($p < 0.01$). Pork color was not affected ($p > 0.05$) by any factor (Table 5).

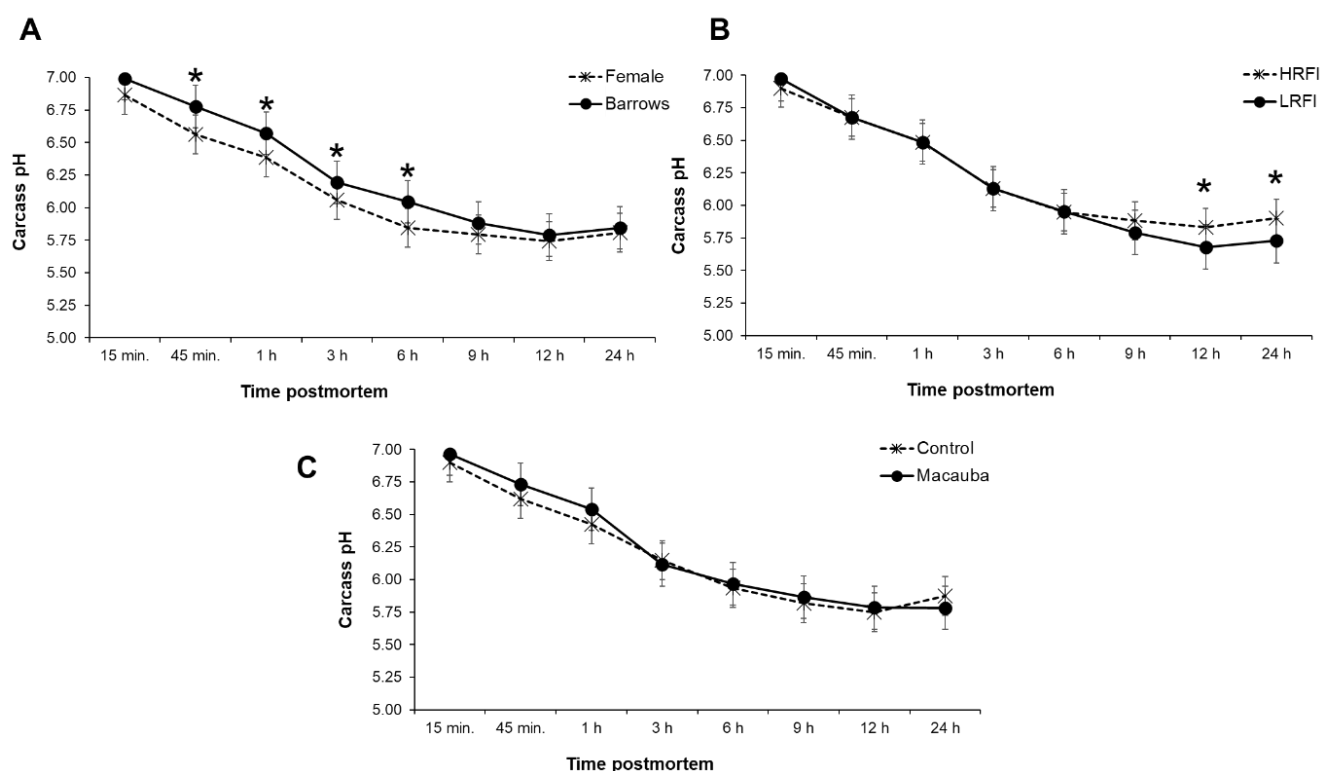


Figure 1. Effect of sex (A); sire breeding value (B); and diet (C) on carcass pH decline during the first 24 h postmortem. Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake. Each vertical bar is the standard error of the mean. * $p < 0.05$.

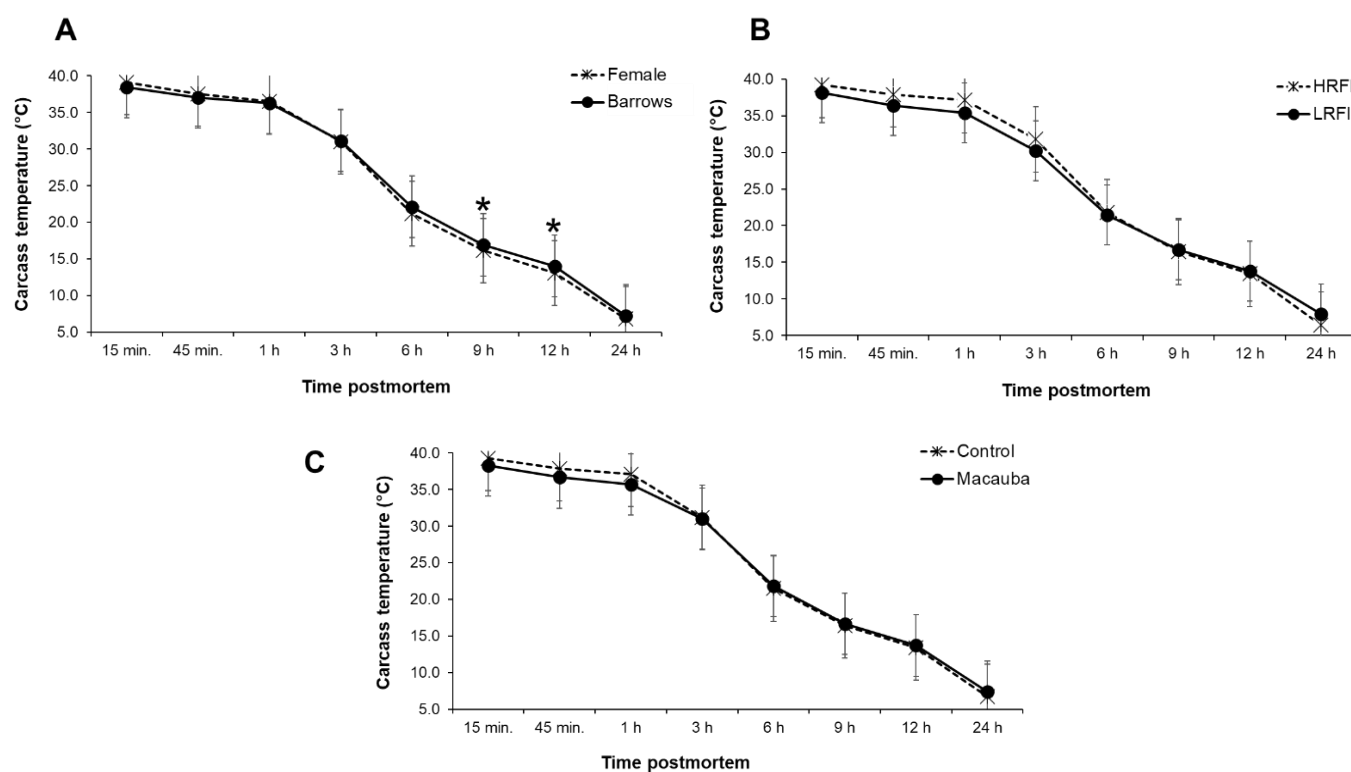


Figure 2. Effect of sex (A); sire breeding value (B); and diet (C) on carcass temperature decline during the first 24 h postmortem. Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake. Each vertical bar is the standard error of the mean. * $p < 0.05$.

Table 5. Effect of sex, sire breeding value, and diet on pork quality parameters of growing-finishing pigs.

Traits	Sex		BV ¹		Diet		RMSE ³	p-Value		
	Barrows	Female	HRFI	LRFI	Control	Macauba ²		Sex	BV	Diet
Experimental units	71	60	74	57	63	68				
Moisture, % FM	71.2	71.5	71.4	71.3	71.5	71.2	0.91	0.08	0.76	0.02
Protein, % DM	25.2	25.4	25.4	25.3	25.3	25.3	0.78	0.09	0.33	0.87
Fat, % DM	2.7	1.9	2.2	2.4	2.2	2.4	1.09	<0.01	0.36	0.21
Ash, % DM	0.9	1.1	0.9	0.9	0.9	1.1	0.32	<0.01	0.91	0.01
Collagen, % DM	0.8	0.7	0.8	0.7	0.7	0.8	0.17	0.35	0.25	0.41
WBSF ⁴ , kgf	3.29	3.49	3.43	3.35	3.38	3.40	0.534	0.03	0.45	0.86
WHC ⁵ , %	88.0	87.8	87.5	88.3	88.6	87.2	2.52	0.55	0.09	<0.01
Cooking loss, %	21.6	21.8	22.1	21.3	21.1	22.2	3.95	0.80	0.26	0.11
Sarcomere length, μ m	1.56	1.55	1.55	1.56	1.56	1.54	0.136	0.46	0.73	0.44
Color parameters										
Lightness (L*)	57.6	57.2	57.2	57.5	57.6	57.2	3.76	0.52	0.67	0.56
Redness (a*)	6.8	6.6	6.7	6.7	6.6	6.8	1.20	0.30	0.45	0.87
Yellowness (b*)	14.8	14.5	14.6	14.7	14.8	14.5	1.84	0.45	0.65	0.45

¹ Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake; ² Inclusion of 50 g/kg of macauba pulp in the diet; ³ Root Mean Square Error; ⁴ WBSF = Warner–Bratzler shear force; ⁵ WHC = Water-holding capacity.

4. Discussion

This study was performed to elucidate the effects of macauba pulp inclusion in diets of growing-finishing pigs on growth performance, as well as on carcass traits and pork quality traits; and whether differences in residual feed intake breeding values could influence pig growth responses to macauba pulp inclusion in the diet.

As there was no interaction between factors, they were discussed independently. There is significant evidence for differences in growth performance between barrows and female pigs, and the present data reaffirm these findings. Generally, at the same slaughtering age, barrows are heavier, grow faster, and have greater feed and energy intake than gilts [29–34]. However, as gilts have a greater ratio of protein accretion relative to lipid accretion, they are also expected to have better feed efficiency than barrows [29,35].

The exact physiological mechanism behind the increased feed intake of barrows is not yet fully elucidated [36]. In the literature, this rise in barrows' feed intake is mostly attributed to behavioral changes resulting from the decrease of gonadal hormones, which reduce aggressive and sexual behaviors, increasing the time spent in feeders, and, thus the feed intake [33,37]. Administration of exogenous gonadal hormones to barrows reduced feed intake [38] and a higher amount of time spent at the feeder in physically castrated pigs compared to intact males and gilts have been reported by Puls et al. [39].

Furthermore, the decline in the maximum protein deposition (PDmax) with increasing live body weight tends to start at a lower live body weight in barrows than in female pigs [40]. According to de Lange et al. [40], the PDmax is lowest in barrows, intermediate in gilts, and highest in boars. In addition, these authors reported that the difference in PDmax between growing-finishing gilts and barrows is approximately 5%. In turn, the PDmax indicates the maximum amount of protein retained in the body and, together with the energy intake, the PDmax regulates the partitioning of energy towards lean and/or fat deposition [41,42]. Therefore, once this plateau is reached, the protein deposition will remain at its greatest level, and an additional rise in energy consumption will solely increase the rates of body lipid deposition, resulting in a fatter carcass and worse feed efficiency [43].

As expected, barrows do not present testosterone's anabolic effect, which has been proven to increase muscle accretion and diminish fat deposition in entire and immunocastrated male pigs before the second vaccination [43,44]. According to Bjorntorp [45], testosterone exerts inhibitory effects on lipoprotein lipase and glycerophosphate dehydro-

genase, turning metabolism towards lipid mobilization and lean deposition. In accordance, our results related fat metabolism as backfat thickness and intramuscular fat are all aligned with that statement.

Overall, visual evaluation of color is driven by the decisions of consumers purchasing meat [46], and tenderness is the most important palatability trait for cooked pork [47]. Also, consumers associate higher pork marbling with a more tender, juicy, and flavorful product [48]. Previous studies have reported that pork tenderness is positively correlated with its intramuscular fat content [49–51] and negatively correlated with the rate and extent of pH decline [47].

In the present study, barrows presented higher intramuscular fat content, as well as lower WBSF and pH decline up to 6 h *postmortem* than female pigs. In agreement, D'Souza and Mullan [52] reported greater tenderness of pork from barrows than from gilts. Although we observed a lower fat content in female pork, the value found was higher than the minimum (1.5%) proposed by Fortin et al. [49] to ensure a satisfying eating experience.

Despite significant improvements in pig management and genetics, feeding still represents the largest cost in a pig production system, arousing great interest in optimizing the use of nutrients by animals [53]. Residual feed intake is a moderately heritable trait, genetically correlated with growth rate and backfat, and is used as a feed efficiency indicator [12]. It is the difference between the observed and predicted feed intake for determined production and maintenance levels, in which a more efficient animal has a lower RFI value [10,54]. Our results demonstrated negligible effects of breeding value on pigs' performance and efficiency. In contrast, Soleimani and Gilbert [55] observed that LRFI line had lower feed intake, daily gain, feed conversion rate, backfat thickness, and lean meat than HRFI line. These divergent responses among studies could be related to the genetic selection process of lineages. In the present study, progenies came from commercial populations ranked according to their RFI, contrasting the experimental data of Soleimani and Gilbert [55] obtained from experimentally selected lines for RFI. In addition, factors such as the methodologies used to measure feed intake, imprecise estimates of the energy content of diets, the weight range used to measure the feeding efficiency, and differences in gain composition can also affect feed efficiency measurement [11,12].

According to Hoque and Suzuki [10], selection for low residual feed intake is expected to favor animals with lower maintenance energy expenditure. Reduced RFI may come from better nutrient and energy utilization efficiency in several functions, such as digestion, intermediary metabolism, and maintenance [9]. Previous studies have reported a positive (unfavorable) genetic correlation between residual feed intake, growth rate, and backfat thickness [9,54–56]. In addition, fat deposition energetic cost is superior to that of protein accretion in muscle [57]. Therefore, it is expected that LRFI pigs would deposit less fat than HRFI pigs due to their lower energy intake [58].

As breeding value did not affect feed intake, animals had similar energy intake. Therefore, the greater backfat thickness of LRFI carcasses may be associated with a decreased maintenance requirement in association with a decreased heat production, lower basal metabolic rate and decreased physical activity [59,60]. According to Gilbert et al. [9], as feed efficiency and energy metabolism are closely related, maybe LRFI pigs muscles present a lower number of mitochondria which in turn have better energy use efficiency. Also, they suggest that reduced Cori cycle rates may play a role in limiting energy expenditure in LRFI pigs. In agreement, Dekkers and Gilbert [54] reported that LRFI pigs have diminished basal maintenance requirements and tissue turnover rates. Faure et al. [58] reported that muscle energy metabolism in HRFI relies on fatty acid and glycogen breakdown, while LRFI pigs mainly relies on glycogen storage and utilization.

Although low and high residual feed intake pigs showed a similar rate and extent of pH and temperature decline, the carcass pH of HRFI pigs stabilized above the LRFI. However, the ultimate pH values were within the range (5.3–5.8) proposed by Smulders et al. [61] for a typical final pH in pig carcasses. In agreement, Faure et al. [58] and Horodyska et al. [62] reported no differences in carcass pH rate and the extent of pigs

divergently selected for RFI. In addition, our results did not evidence differences in quality traits of pork between LRFI and HRFI pigs. These findings are in agreement with those reported by Cai et al. [56] and Smith et al. [63].

The pigs showed no signs of objection to, or gastrointestinal complications from, the macauba-containing diets, and the performance and carcass traits were similar between dietary treatments. However, when evaluating by phases, it is evident that macauba pulp inclusion improved feed efficiency in finishing phase 2 and that this co-product did not affect any growth parameter during the first three growth phases. In agreement, Dias et al. [7] reported that, up to 100 g/kg of inclusion, macauba pulp did not affect the performance and body composition of growing pigs, and Costa Júnior et al. [8] reported that the inclusion of 50 g/kg of macauba pulp in finishing pigs' diet improved their feed efficiency.

Dietary fiber digestibility has been shown to ameliorate with increasing pigs' body weight [64–66]. Several causes could explain it, including a longer retention time, a decrease in feeding level relative to BW, a greater intestinal volume, and a better capacity of hindgut flora to digest fiber [67]. Thus, the reduced feed intake and better feed efficiency observed in finishing pigs fed the macauba diet may be explained by the better use of dietary fiber [68].

Pork quality and palatability are dependent on properties such as WHC, oxidative stability, and color, which are critical for processing and storage [69]. In addition, these pork attributes are primarily determined by *postmortem* changes, such as the rate and extent of pH decline, proteolysis, and protein oxidation [70–72]. The lower the muscle pH, the lower its ability to retain water, increasing liquid loss during cooking, which may negatively affect pork tenderness, juiciness, and color [73,74].

In the present study, macauba pulp inclusion did not influence the rate or extent of carcass pH decline, or the color, tenderness, and loss of liquid during the cooking of pork. However, pork from pigs fed the macauba diet showed lower WHC and moisture compared to pigs fed the control diet. Huff-Lonergan and Lonergan [75] reported that WHC variation at a given storage pH and temperature is supposedly due to alterations in proteolysis and consequent muscle cell shrinkage, by the expulsion of water into the extracellular space. According to Savell et al. [70] and den Hertog-Meischke et al. [73], as the pH drops, all the negatively and positively charged filaments become equal, reducing the repulsion between them. This maximal attraction diminishes the space between filaments, holding them close together, not allowing water to enter, and decreasing the WHC. However, because we did not evaluate the denaturation of muscle protein, we were unable to conclude that the inclusion of 50 g/kg of macauba pulp was responsible for the decreased stability of water in the muscles. However, these WHC and moisture values in pigs fed the macauba pulp diet are in accordance with previous studies [76–78].

5. Conclusions

In conclusion, macauba pulp (*Acrocomia aculeata*) showed great potential as an alternative feedstuff in pigs' diets. It was evident that feeding pigs with this co-product did not affect growth performance during growing phases 1 and 2, and finishing phase 1, resulting in improved feed efficiency in finishing phase 2. In addition, it did not influence the carcass traits, fat and protein content, tenderness, color, and cooking loss of pork, indicating that pork from macauba-fed pigs will have a similar acceptability as pork from pigs fed a conventional corn and soybean meal-based diet. The results of this study suggest that regardless of sex and breeding value for RFI, pigs respond similarly to macauba pulp inclusion in their diets.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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