South African Journal of Animal Science 2026, vol. 56(3)

Effect of the beta-adrenergic agonists, ractopamine hydrochloride and salbutamol, on the performance of finisher pigs

J.P. de Jager[1], W.J. Steyn[1,2], E.A. Akuru[1#], R.J. Coertze[1], & C. Jansen van Rensburg[1]

[1]Department of Animal Science, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa
[2]SwiNE Nutrition Management, Pretoria, South Africa

(Submitted 20 June 2025; Accepted 13 January 2026; Published 13 March 2026)

Abstract

The efficacy and safety of beta-adrenergic agonist use in modern swine production are controversial. This study aimed to determine the effect of dietary ractopamine hydrochloride and salbutamol on the performance of 440 male and female finisher pigs (Topigs Norsvin TN70), housed in 40 pens of 11 animals each, with five treatments and four replicates per treatment. The dietary treatments included a negative control, containing 16% crude protein and no feed additives; ractopamine-16 (negative control plus 6 mg ractopamine/kg); ractopamine-13 (13% crude protein and similar essential amino acid concentrations to the negative control, plus 6 mg ractopamine/kg); salbutamol-6 (negative control plus salbutamol 10% at 6 mg/kg); and salbutamol-4 (negative control plus salbutamol 10% at 4 mg/kg). At 6 mg/kg feed, ractopamine had no effect on pigs' growth and carcass indices compared to the negative control, regardless of the dietary crude protein concentration. However, gilt carcasses had lower lean percentages on the ractopamine-13 diet than on the negative control diet. Pigs fed 4 mg and 6 mg salbutamol/kg had higher lean percentages than the negative control group. The crude protein content of a diet containing ractopamine can thus be decreased from 16% to 13% for boars, whereas gilts may still benefit from a higher crude protein concentration. Salbutamol supplementation suppressed feed intake and growth in boars and enhanced feed efficiency and lean percentage in gilts. Hence, salbutamol supplementation at 4 mg/kg may be a viable alternative to ractopamine for finisher pigs, producing a higher lean percentage and return on investment, and reduced production costs, despite not enhancing growth.

Keywords: carcass modifiers, lean carcasses, nutrient partitioning, pork quality, sustainability

#Corresponding author: eunice.akuru@up.ac.za

Introduction

Worldwide, the pig industry is steering towards the production of heavier but leaner carcasses. In South Africa, for instance, the PORCUS classification system has been developed to categorise pig carcasses based on the thickness of the backfat and the percentage of lean meat. This system rewards the production of leaner pigs by awarding a higher classification and price to carcasses with the highest percentage of lean meat (Soji *et al.,* 2015). However, the system fails to adequately address

URL: www.sajas.co.za
ISSN 0375-1589 (print), ISSN 2221-4062 (online)
Publisher: South African Society for Animal Science
https://doi.org//10.17159/sajas.v56i03.02

sustainability and safety concerns, thereby ignoring the increasing interest of consumers in safe products that also meet animal well-being criteria.

Beta-agonists such as ractopamine hydrochloride have been used as feed supplements to increase weight gain and feed efficiency, reduce fat tissue accretion, and improve carcass dressing percentage and quality. At higher dietary inclusion levels, they may also enhance carcass leanness by redirecting nutrients away from adipose tissue and towards muscle growth (Halsey *et al.*, 2011; de Almeida *et al.*, 2012; Marcolla *et al.*, 2017; Ferreira *et al.*, 2017; Costa *et al.*, 2018; Abbas *et al.*, 2022; Elanco, 2023). However, concerns remain regarding the safety of ractopamine for both the animal and the consumer (Zaitseva *et al.*, 2014; Abbas *et al.*, 2022), based on reports of increased excitement and aggression in animals fed this supplement (Marchant-Forde, 2003; Poletto *et al.*, 2010). This has led to its ban in China and the European Union (Needham *et al.*, 2017), despite reports of minimal effects on mortality rates (Ritter *et al.*, 2017) and evidence that it increases lipolysis and reduces the intramuscular fat content of pork (Martins *et al.*, 2015; Ferreira *et al.*, 2017).

Despite these safety concerns and bans by some countries, ractopamine was the first beta-agonist receptor ligand to be approved for swine by the United States Food and Drug Agency (FDA) in 1999 (FDA, 1999; Abbas *et al.*, 2022). On 5 July 2012, the first-ever maximum residue levels (MRLs) for ractopamine were adopted by the Codex Alimentarius Commission as 10 µg/kg for pork and beef (Alfredo *et al.*, 2017). Hence, the use of ractopamine is approved in swine, cattle, and turkey diets in the United States, which is the third largest producer of pork worldwide (Arp *et al.*, 2014; Centner *et al.*, 2014; Abbas *et al.*, 2022). Ractopamine use is also permitted in Canada, Japan, South Korea, Brazil, Mexico, and South Africa, as regulators in these countries have deemed meat produced by pigs and cattle fed dietary ractopamine safe for human consumption (de Almeida *et al.*, 2012; Pacelle, 2014; Jaurez *et al.*, 2016; Ritter *et al.*, 2017; Park *et al.*, 2019; Abbas *et al.*, 2022). Ractopamine is currently authorised as an acceptable feed additive in the pig and cattle industries in many countries, based on the recommendations of the joint Food and Agriculture Organization (FAO)/World Health Organization (WHO) Expert Committee on Food Additives and Scientific Evidence (Needham *et al.*, 2017; Abbas *et al.*, 2022), with some countries stipulating MRLs (FAO, 2012; Needham *et al.*, 2017; Abbas *et al.*, 2022).

In South Africa, beta-agonists have been used to improve meat production for the past 25 years (Webb *et al.*, 2018). Ractopamine is registered in South Africa for use in swine and cattle under the trade name Paylean™ (Elanco, 2023), and Needham *et al.* (2017) reported improved average daily gains (ADG) in male pigs when 10 mg ractopamine/kg was added to the finisher feed. A significant interaction between ractopamine inclusion and dietary crude protein (CP) concentration was also noted, with medium (20% CP, 9.8 g/kg standardised ileal digestible lysine (SID Lys)) and high (25% CP, 12.07 g/kg SID Lys) CP diets resulting in improved feed conversion efficiency compared to a low (16% CP, 7.5 g/kg SID Lys) CP diet. Considering the market value and current authorisation of the use of ractopamine in 27 countries, ractopamine inclusion in pig diets still has the potential to enhance the efficiency of large-scale commercial pork production (Needham *et al.*, 2017).

Salbutamol, a prescription drug used to relieve breathing difficulties in humans, also acts as a repartitioning agent in pigs (Marchant-Forde *et al.*, 2012). Existing literature has demonstrated the positive effects of R-salbutamol supplementation at inclusion levels as low as 2 mg/kg on growth and carcass characteristics in pigs (Marchant-Forde *et al.*, 2012). Salbutamol was registered for use in swine diets in South Africa in 2021 as Salbutamate 10%, having previously been registered in 2014 and 2017 for use in cattle and sheep diets, respectively. The South African supplier of salbutamol (Animate Animal Health, 2021) claims that it has no adverse effects on meat quality and has the potential to ensure sustainable and high-quality meat production. The supplier recommends an inclusion level of 2–6 mg/kg feed during the last 28 days of the finishing phase, with no withdrawal period required in pigs. Several studies have been conducted on the supplementation of salbutamol to South African feedlot cattle (Webb *et al.*, 2023) and sheep (de Klerk *et al.*, 2016; du Toit *et al.*, 2017), but no studies on South African swine could be found.

The FDA approved the use of ractopamine supplemented at 4.5–9.0 mg/kg in feed that contains at least 16% CP for finisher pigs heavier than 68 kg for the last 20–40 kg of weight gain prior to slaughter (FDA, 2006). However, over recent years, the pork industry has made significant genetic advancements (Wu & Bazer, 2019), and it is therefore possible that current commercial pigs, with their high potential for fast lean tissue deposition and high feed efficiency, do not benefit from the continued use of expensive beta-agonist agents. It is therefore pertinent to ascertain whether the use of beta-agonists is still relevant in the nutrition of the modern pig. Furthermore, lower CP diets are often implemented to reduce production costs and minimise environmental pollution. These are generally nutritionally adequate, provided that the requisite amino acids are present in appropriate and balanced proportions (Åkerfeldt *et al.*, 2019; Rocha *et al.*, 2022). Rocha *et al.* (2022) showed that when diets were balanced for all essential amino acids, the growth performance and feed conversion efficiency of finisher pigs could be sustained, if the dietary CP concentration was maintained above 11.6% and 11.4%, respectively. However, ractopamine enhances lean meat accretion, which naturally increases the requirement for amino acids. Many studies have shown that ractopamine-supplemented pigs often benefit from a higher dietary lysine concentration (Andretta *et al.*, 2012; Needham *et al.*, 2017). However, no study can be found that addresses whether the recommendation of 16% dietary CP with ractopamine supplementation is still valid, or whether the total CP concentration, and thus the concentrations of the non-essential amino acids, can be reduced if the concentrations of essential amino acids are kept sufficiently high.

Considering the beneficial effects of ractopamine and salbutamol supplementation in pigs, it was hypothesised that dietary ractopamine and salbutamol have the potential to elicit significant improvements in the performance parameters of pigs, and that dietary salbutamol can be considered as a viable alternative to ractopamine in pig diets. It was also hypothesised that the recommendation of 16% total CP inclusion in a diet containing ractopamine is outdated, and that the CP concentration could be reduced if the levels of essential amino acids are kept constant.

To test these hypotheses, this study was conducted to assess the suitability of the continued use of ractopamine and salbutamol in enhancing performance and modifying carcass parameters in the modern commercial pig, specifically Topigs Norsvin TN70. The study also aimed to determine the impact of reducing the dietary CP concentration from the recommended inclusion level (16%) to a lower level (13%), while maintaining equal levels of essential amino acids, on the performance of finisher pigs supplemented with ractopamine. Furthermore, in view of the recent approval of salbutamol use in pigs in South Africa, the effects of ractopamine and salbutamol on the growth performance and carcass characteristics of finisher pigs were compared.

Materials and methods

The study was conducted at the Baynesfield Swine Research Unit (BSRU) on the Baynesfield Estate Piggery, in KwaZulu-Natal, South Africa. The study location is known for its tropical and humid climate. The area experiences high rainfall between October and March, which are summer months, and has a daily temperature range of 20 °C to 35 °C. Experimental procedures were in line with the ethical approval obtained from the Animal Ethics Committee of the University of Pretoria, with ethical clearance number: NAS128/2022.

Four hundred and forty (440) 70-day-old Topigs Norsvin TN70 × Tempo grower pigs, with equal numbers of boars and gilts, were sourced from the weaner unit at Baynesfield Estate Piggery and moved to a pig grower house on the same site. The house had open sides with automatically controlled curtains that opened and closed to achieve the desired temperature and air flow. There were 40 numbered group pens, divided into four equal blocks with 10 pens in each block. Boars and gilts were randomly divided into separate pens with 11 pigs per pen at a stocking density of 1 m^2 per pig. Each pen served as an experimental unit and all pigs were ear-tagged with a unique number. Feed and water were provided *ad libitum* by one Rotechna TR2 feeder per pen and two water nipples per pen. Each TR2 feeder had two 28 cm wide outlets. The same feed was fed to all the pigs from the point of placement at 70 days old until the end of the grower phase at 120 days old (Table 1). The initial body weights of the pigs at 120 days of age did not differ significantly between any of the pens, indicating that the pigs were not influenced by any factors during the pre-trial phase, before the initiation of the dietary treatments.

Five treatment diets (Table 2) were introduced at the start of the finisher phase (at 120 days of age) and were fed until the pigs were slaughtered at 154 days of age. The five dietary treatments fed to the finisher pigs were as follows:

1. Negative control (NC): A diet containing no additives and 16% CP, with 9.9 g SID Lys/kg.
2. Ractopamine-16: The NC diet (16% CP) plus ractopamine included at 6 mg/kg of feed.
3. Ractopamine-13: A finisher diet containing 13% CP and essential amino acid concentrations similar to those of the NC diet, with ractopamine included at 6 mg/kg of feed.
4. Salbutamol-6: The NC diet (16% CP) plus salbutamol 10% included at 6 mg/kg.
5. Salbutamol-4: The NC diet (16% CP) plus salbutamol 10% at 4 mg/kg.

Table 1 Ingredients and nutrient composition of pig grower diets fed from 70–120 days of age (during the pre-trial phase)

Feed ingredients (kg/t)	Grower 1 (days 70–90)	Grower 2 (days 90–105)	Grower 3 (days 105–120)
Maize	703	702	689
Wheat bran	89.8	100	130
Soya oil cake	132	115	102
Sunflower oil cake	38.8	50.0	50.0
Limestone	12.9	12.7	12.8
Mono-dicalcium phosphate	4.52	3.45	2.75
Salt	4.04	4.81	4.79
Lysine hydrochloride	6.79	5.24	3.62
DL-methionine	2.99	2.11	1.24
L-threonine	2.16	1.33	0.78
L-tryptophan	0.80	0.53	0.25
Grower premix[1]	1.62	1.62	1.62
AxtraPHY 10 000 TPT[2]	0.10	0.10	0.10
Axtra XB[3]	0.10	0.10	0.10
Calculated nutrient composition (g/kg unless otherwise indicated)			
Net energy (MJ/kg)	9.70	9.60	9.55
Crude protein	155	150	145
Fat	36.0	36.0	36.2
Crude fibre	34.7	37.6	40.0
Calcium	7.50	7.00	6.60
Sodium	2.00	2.30	2.30
Digestible phosphorus	3.20	3.00	2.90
Standardised ileal digestible lysine	10.9	9.40	7.90
Standardised ileal digestible lysine: Net energy	1.12	0.98	0.83

[1]Grower premix provided (per kg of feed): 8 000 000 IU vitamin A, 1 000 000 IU vitamin D_3, 85 000 mg vitamin E, 2000 mg vitamin K_3, 1500 mg vitamin B_1, 3500 mg vitamin B_2, 2500 mg vitamin B_6, 35 mg vitamin B_{12}, 25 000 mg vitamin B_3, 15 000 mg vitamin B_5, 500 mg folic acid, 50 mg biotin, 150 000 mg choline chloride, 30 000 mg manganese sulphate, 75 000 mg iron sulphate, 100 000 mg zinc sulphate, 0 mg zinc oxide, 150 000 mg copper sulphate, 1500 mg iodine, 300 mg selenium. [2]Phytase feed enzymes (New York, USA). [3]Non-starch polysaccharide-degrading enzymes (New York, USA).

The inclusion of R-salbutamol sulphate (Salbutamate® 10%) was based on the supplier's (Animate Animal Health) recommendation that the supplement should be included in the diets of pigs at 5–18 mg/pig/day (or 2–6 mg/kg of feed), with higher efficacy linked to higher inclusion rates. In previous studies, R-salbutamol was fed to finisher pigs at 2 mg/kg, 4 mg/kg, and 8 mg/kg (Marchant-Forde *et al.*, 2008, 2012). In the present study, the chosen inclusion levels (4 mg/kg and 6 mg/kg) were within the recommended levels and aligned with the levels reported in previous studies. Future studies can explore higher levels of salbutamol inclusion in finisher pigs' diets. All treatment diets were similar in nutrient specifications, except for the ractopamine-13 diet, which had a lower CP concentration of 13% but similar essential amino acid concentrations to the NC diet (Table 2).

During the trial, the performance of the pigs was measured at the end of the grower phase/start of the finisher phase (120 days of age) and the end of the finisher phase (154 days of age). The feed fed weekly per pen was weighed and divided by the number of animals per pen to determine the mean feed intake (in kg). Pigs were weighed individually once a week, and the ADG was then calculated. Mortality records were kept throughout the trial. The feed conversion ratio (FCR) was calculated by dividing the feed intake of a pen over a period by the total weight gain of pigs in that pen over the same period. The FCR was corrected for mortalities.

Table 2 Ingredients and nutrient composition of five treatment diets fed to pigs during the finisher phase from 120–154 days of age (trial phase)

Feed ingredients (kg/t)	NC[6]	Ractopamine -16[7]	Ractopamine -13[8]	Salbutamol-6[9]	Salbutamol-4[10]
Maize	718	718	750	718	718
Wheat bran	71.4	71.4	100	71.4	71.4
Sunflower oil cake	132	132	68.0	132	132
Sunflower oil	50.0	50.0	50.0	50.0	50.0
Limestone	9.35	9.35	9.88	9.35	9.35
Mono-dicalcium phosphate	3.02	3.02	3.43	3.02	3.02
Salt	4.11	4.11	3.54	4.11	4.11
Lysine hydrochloride	5.45	5.45	7.34	5.45	5.45
DL-methionine	2.31	2.31	2.91	2.31	2.31
L-threonine	1.53	1.53	2.39	1.53	1.53
L-tryptophan	0.43	0.43	0.72	0.43	0.43
Ractopamine HCl[1]	-	0.30	0.30	-	-
Finisher premix[2]	1.30	1.30	1.30	1.30	1.30
Axtra XB[3]	0.10	0.10	0.10	0.10	0.10
AxtraPHY 10 000 TPT[4]	0.10	0.10	0.10	0.10	0.10
Salbutamate 10%[5]	-	-	-	0.60	0.04
Calculated nutrient concentrations (g/kg unless otherwise indicated)					
Net energy (NE, MJ/kg)	9.80	9.80	9.80	9.80	9.80
Crude protein	155	155	135	155	155
Fat	36.2	36.2	36.5	36.2	36.2
Crude fibre	35.5	35.5	36.6	35.5	35.5
Calcium	6.00	6.00	6.10	6.00	6.00
Sodium	2.02	2.02	1.8	2.02	2.02
Digestible phosphorus	2.90	2.90	2.90	2.90	2.90
SID Lys	9.90	9.90	9.90	9.90	9.90
SID Lys:NE	1.01	1.01	1.01	1.01	1.01

[1]Ractopamine hydrochloride: Paylean, Elanco Animal Health, Greenfield, IN; [2]Finisher premix provided (per kg of feed): 6 000 000 IU vitamin A, 1 000 000 IU vitamin D_3, 40 000 mg vitamin E, 1500 mg vitamin K_3, 1500 mg vitamin B_1, 3000 mg vitamin B_2, 2000 mg vitamin B_6, 25 mg vitamin B_{12}, 20 000 mg vitamin B_3, 15 000 mg vitamin B_5, 0 mg folic acid, 0 mg biotin, 100 000 mg choline chloride, 25 000 mg manganese sulphate, 75 000 mg iron sulphate, 80 000 mg zinc sulphate, 0 mg zinc oxide, 100 000 mg copper sulphate, 1000 mg iodine, 300 mg selenium. [3]Non-starch polysaccharide-degrading enzymes (New York, USA). [4]Phytase feed enzymes (New York, USA). [5]Salbutamate 10%: Animate Animal Health, Gauteng, South Africa. [6]NC: negative control (no additives, 16% crude protein). [7]Ractopamine-16: 6 mg ractopamine/kg, 16% crude protein. [8]Ractopamine-13: 6 mg ractopamine/kg, 13% crude protein. [9]Salbutamol-6: 6 mg salbutamol/kg, 16% crude protein. [10]Salbutamol-4: 4 mg salbutamol/kg, 16% crude protein. SID Lys: standardised ileal digestible lysine.

At the end of the trial (day 154), all pigs were euthanised and slaughtered at Frey's Food Brands abattoir, Cato Ridge, KwaZulu-Natal. Warm carcass weight, cold carcass weight, carcass moisture loss, lean meat percentage, and dressing percentage were recorded. The Hennessy Grading Probe, a durable, handheld electronic and optical device connected to a computer system that uses reflectance spectroscopy, was used to measure the lean meat percentage. Fat thickness and eye muscle thickness were measured on a hanging carcass with the probe positioned between the second- and third-last ribs, 45 mm from the mid-back line, as described by Steyn *et al.* (2012). The following formula, proposed by Visser (2004), was used to calculate the lean meat percentage:

$$Henessy\ \%\ lean = 72.5114 - (0.4618 \times fat\ thickness) + (0.057 \times eye\ muscle\ thickness)$$

The carcass classification system used in this study was based on the South African PORCUS classification system used at the time of the trial. The return on investment (ROI) per pig was calculated using the following formula:

$$Feed\ cost\ (ZAR/pig) = \ Feed\ price\ (ZAR/kg) \times Totalfeed\ intake\ (kg/pig)$$

The feed cost was calculated per phase and summed to calculate the total cost per treatment. Revenue was then determined by multiplying the average cold carcass weight by the value of the meat (ZAR/kg) per treatment. The ROI (ZAR/pig) was calculated by subtracting the total cost of feed from the revenue (ZAR/pig) and was calculated per pig per treatment.

Data were analysed using the Proc Mixed model (Statistical Analysis System, 2021) for the average effects. Means and standard errors were calculated, and the significance of the difference (P <0.05) between means was determined using Fisher's test (Samuels, 1989). Repeated measures analysis of variance with a mixed model was used for repeated week or period measures. The following equation describes the linear mixed model used:

$$Y_{ijk} = \mu + T_i + S_j + B_k + TS_{ij} + TS_{ik} + e_{ijk}$$

where: Y_{ijk} = variable studied during the period, μ = overall mean of the population, T_i = effect of the i^{th} treatment, S_j = effect of the j^{th} sex, B_k = effect of the k^{th} block (four equal blocks per treatment), TS_{ij} = effect of the ij^{th} interaction between treatment and sex, and e_{ijk} = error associated with each Y.

The male and female pigs were individually weighed, divided, separated, randomised, and blocked into 40 numbered group pens of 11 animals each, with four replicates per sex for each of the five dietary treatments. Each pen served as an experimental unit. The pens were divided into four equal blocks, with each block consisting of ten pens of five treatments with two sexes per treatment. Sex, treatment, and block were the fixed effects, while pen was the random effect. The averages of the pens were used to determine differences, and testing was done within the sexes between the treatments and not between the sexes.

Carcass classification data were analysed statistically using the Proc Freq model (Statistical Analysis System, 2023) for the chi-square test, frequencies were calculated, and the significance of the differences (P <0.05) were determined using Fisher's test (Samuels, 1989).

Results

Results in Table 3 show that the body weight gain and ADG of boars fed the 16% CP and 13% CP ractopamine diets were comparable (P >0.05) to those of the boars fed the NC diet. Final body weights did not differ (P >0.05) between groups, regardless of the dietary treatment. The same trend of comparable (P >0.05) dietary effects was observed for the feed intake and FCR of gilts and boars fed the ractopamine-16, ractopamine-13, and NC diets. Gilts and boars fed the salbutamol-6 diet had lower (P >0.05) feed intakes than the NC pigs, whereas comparable (P >0.05) FCR values were recorded for the two salbutamol dietary groups. Body weight gain and ADG were lower (P <0.05) in boars fed salbutamol-6 than boars fed the NC diet, whereas performance indicators were comparable (P >0.05) between pigs fed diets containing high and low salbutamol concentrations.

Table 3 Effects of ractopamine hydrochloride and salbutamol on the performance (mean ± standard error) of finisher pigs at 120–154 days of age

Treatments	Beta-agonist dosage	CP %	Treatment effect	Interaction effect[1]	
				Male	Female
Initial body weight (kg)					
Negative control	-	16	74.86	74.22	75.50
Ractopamine-16	Ractopamine (6 mg/kg)	16	73.77	72.42	75.12
Ractopamine-13	Ractopamine (6 mg/kg)	13	75.05	73.40	76.69
Salbutamol-6	Salbutamol (6 mg/kg)	16	76.03	76.05	76.02
Salbutamol-4	Salbutamol (4 mg/kg)	16	73.73	72.36	75.11
Standard error			0.677	0.958	0.958
***P*-value**			0.158	0.516	
Final body weight (kg)					
Negative control	-	16	116.0	115.8	116.2
Ractopamine-16	Ractopamine (6 mg/kg)	16	114.0	113.2	114.7
Ractopamine-13	Ractopamine (6 mg/kg)	13	115.4	114.0	116.8
Salbutamol-6	Salbutamol (6 mg/kg)	16	114.5	113.3	115.6
Salbutamol-4	Salbutamol (4 mg/kg)	16	114.0	112.7	115.4
Standard error			1.145	1.619	1.619
***P*-value**			0.710	0.955	
Body weight gain (kg)					
Negative control	-	16	41.13^{a}	41.60^{a}	40.65
Ractopamine-16	Ractopamine (6 mg/kg)	16	40.39^{ab}	41.19^{a}	39.58
Ractopamine-13	Ractopamine (6 mg/kg)	13	40.31^{ab}	40.55^{ab}	40.07
Salbutamol-6	Salbutamol (6 mg/kg)	16	38.27^{b}	37.51^{b}	39.03
Salbutamol-4	Salbutamol (4 mg/kg)	16	40.28^{ab}	40.30^{ab}	40.26
Standard error			0.877	1.240	1.240
***P*-value**			0.323	0.870	
Average daily gain (kg)					
Negative control	-	16	1.18^{a}	1.19^{a}	1.16
Ractopamine-16	Ractopamine (6 mg/kg)	16	1.16^{ab}	1.18^{a}	1.13
Ractopamine-13	Ractopamine (6 mg/kg)	13	1.15^{ab}	1.16^{ab}	1.14
Salbutamol-6	Salbutamol (6 mg/kg)	16	1.10^{b}	1.07^{b}	1.12
Salbutamol-4	Salbutamol (4 mg/kg)	16	1.15^{ab}	1.15^{ab}	1.15
Standard error			0.025	0.035	0.035
***P*-value**			0.323	0.870	
Total feed intake (kg)					
Negative control	-	16	107.1^{a}	104.9^{ab}	109.2^{a}
Ractopamine-16	Ractopamine (6 mg/kg)	16	104.6^{ab}	103.0^{ab}	106.2^{ab}
Ractopamine-13	Ractopamine (6 mg/kg)	13	109.2^{a}	106.6^{a}	111.8^{a}
Salbutamol-6	Salbutamol (6 mg/kg)	16	96.2^{c}	93.40^{c}	98.9^{c}
Salbutamol-4	Salbutamol (4 mg/kg)	16	99.8^{bc}	99.0^{bc}	100.5^{bc}
Standard error			1.70	2.40	2.40
***P*-value**			<0.000	0.740	

[a-c] Means within columns with different superscripts are significantly different (P <0.05). [1]Testing was done within the sexes between the treatments and not between the sexes. CP: dietary crude protein concentration.

Table 3 (continued)

Treatments	Beta-agonist dosage	CP %	Treatment effect	Interaction effect[1]	
				Male	Female
Feed conversion ratio (g/g)					
Negative control	-	16	2.64[ab]	2.56	2.73[ab]
Ractopamine-16	Ractopamine (6 mg/kg)	16	2.62[ab]	2.51	2.72[ab]
Ractopamine-13	Ractopamine (6 mg/kg)	13	2.74[a]	2.66	2.82[a]
Salbutamol-6	Salbutamol (6 mg/kg)	16	2.55[b]	2.55	2.56[b]
Salbutamol-4	Salbutamol (4 mg/kg)	16	2.51[b]	2.50	2.52[b]
Standard error			0.053	0.75	0.75
***P*-value**			0.034	0.607	

[a-c] Means within columns with different superscripts are significantly different (*P* <0.05). [1]Testing was done within the sexes between the treatments and not between the sexes. CP: dietary crude protein concentration.

Compared to the NC diet, reducing or increasing dietary CP levels had no effects (*P* >0.05) on the carcass performance indicators of either gilts or boars fed ractopamine hydrochloride (Table 4). No differences (*P* >0.05) between the treatment groups were observed in the warm and cold carcass weights and dressing percentages (Table 4). Gilts fed the ractopamine-16 diet had a comparable (*P* >0.05) lean percentage to those fed the ractopamine-13 diet, whereas the gilts in the NC group had higher lean percentages (*P* <0.05) than those in the ractopamine-13 dietary group. The lean percentage in boars did not differ between the high and low CP ractopamine diets (*P* >0.05). Gilts fed the 6 mg/kg salbutamol diet had similar (*P* >0.05) lean percentages to those fed the 4 mg/kg salbutamol diet and the NC diet.

Table 4 Effects of ractopamine hydrochloride and salbutamol supplementation from 120–154 days of age on the carcass traits (mean ± standard error) of finisher pigs

Treatments	Beta-agonist dosage	CP %	Treatment effect	Interaction effect[1]	
				Male	Female
Warm carcass weight (kg)					
Negative control	-	16	91.53	90.10	92.96
Ractopamine-16	Ractopamine (6 mg/kg)	16	89.68	87.91	91.45
Ractopamine-13	Ractopamine (6 mg/kg)	13	90.98	88.46	93.49
Salbutamol-6	Salbutamol (6 mg/kg)	16	91.10	88.61	93.49
Salbutamol-4	Salbutamol (4 mg/kg)	16	90.91	88.36	93.46
Standard error			1.043	1.474	1.474
***P*-value**			0.831	0.811	
Cold carcass weight (kg)					
Negative control	-	16	87.99	86.70	89.28
Ractopamine-16	Ractopamine (6 mg/kg)	16	86.40	84.85	87.95
Ractopamine-13	Ractopamine (6 mg/kg)	13	87.62	85.24	89.99
Salbutamol-6	Salbutamol (6 mg/kg)	16	87.66	85.34	89.98
Salbutamol-4	Salbutamol (4 mg/kg)	16	87.75	85.27	90.23
Standard error			1.026	1.451	1.451
***P*-value**			0.899	0.862	

[a-d] Means with different superscripts are significantly different (*P* <0.05). [1]Testing was done within the sexes between the treatments and not between sexes. CP: dietary crude protein concentration.

Table 4 (continued)

Treatments	Beta-agonist dosage	CP %	Treatment effect	Interaction effect[1]	
				Male	Female
Dressing percentage (%)					
Negative control	-	16	78.93	77.83	80.03
Ractopamine-16	Ractopamine (6 mg/kg)	16	78.69	77.65	79.72
Ractopamine-13	Ractopamine (6 mg/kg)	13	78.84	77.63	80.05
Salbutamol-6	Salbutamol (6 mg/kg)	16	79.52	78.20	80.84
Salbutamol-4	Salbutamol (4 mg/kg)	16	79.73	78.45	81.01
Standard error			0.346	0.490	0.490
***P*-value**			0.252	0.546	
Lean percentage (%)					
Negative control	-	16	69.27^{cd}	69.10	69.44^{ab}
Ractopamine-16	Ractopamine (6 mg/kg)	16	69.54^{bc}	69.34	69.73^{bc}
Ractopamine-13	Ractopamine (6 mg/kg)	13	69.15^{d}	69.30	68.98^{c}
Salbutamol-6	Salbutamol (6 mg/kg)	16	69.91^{a}	69.51	70.30^{a}
Salbutamol-4	Salbutamol (4 mg/kg)	16	69.67^{ab}	69.65	69.72^{ab}
Standard error			0.156	0.220	0.220
***P*-value**			0.015	0.208	

[a-d] Means with different superscripts are significantly different (P <0.05). [1]Testing was done within the sexes between the treatments and not between sexes. CP: dietary crude protein concentration.

The results of the probability of a significant difference in the frequency of carcass classification are shown in Table 5.

Table 5 Effects of dietary beta-agonists on pig carcass classifications according to the South African PORCUS[1] classification system (pooled data)

Treatments	Beta-agonist dosage	CP (%)	Distribution			Total
				P+O	R+C	
Negative control	-	16	Frequency	68.0	19.0	87
			% P+O vs R+C	78.2	21.8	
Ractopamine-16	Ractopamine (6 mg/kg)	16	Frequency	74.0	11.0	85
			% P+O vs R+C	87.1	12.9	
Ractopamine-13	Ractopamine (6 mg/kg)	13	Frequency	72.0	15.0	87
			% P+O vs R+C	82.8	17.2	
Salbutamol-6	Salbutamol (6 mg/kg)	16	Frequency	77.0	7.00	84
			% P+O vs R+C	91.7	8.30	
Salbutamol-4	Salbutamol (4 mg/kg)	16	Frequency	80.0	6.00	86
			% P+O vs R+C	93.0	7.00	

[1]P: lean meat percentage ≥70%. O: lean meat percentage 68%–69%; R: lean meat percentage 66%–67%; C: lean meat percentage 64%–65%. Chi-square P-value = 0.024. CP: dietary crude protein concentration.

The P and O classes and the R and C classes were grouped, as these classifications tend to receive the same price per kilogram. Pigs fed the low and high concentrations of salbutamol had more carcasses classed in the P+O grouping (80 and 77, respectively) than pigs in the NC group (68). This test was significant and showed that the ractopamine-16 treatment yielded 87.1% P+O carcasses and

12.9% R+C carcasses, compared to the 93.0% P+O carcasses and 7.0% R+C carcasses recorded for the salbutamol-4 group. For ractopamine-13 pigs, 87.8% of carcasses received a P+O classification and 17.2% received an R+C classification, compared to 91.7% and 8.3%, respectively, for salbutamol-6 pigs.

The effects of ractopamine hydrochloride and salbutamol on the ROI are shown in Figure 1. The 4 mg salbutamol/kg diet yielded the highest and best ROI, compared to the ractopamine-16 group (P = 0.0135). The other dietary groups also had higher ROI values than the ractopamine-16 dietary group.

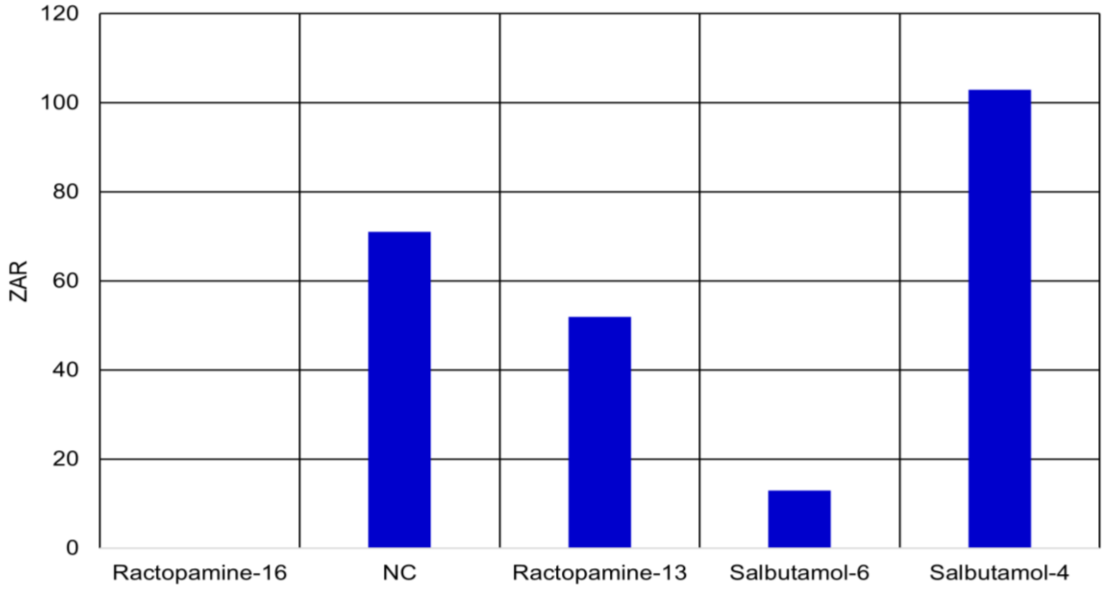

Figure 1 The effect of ractopamine hydrochloride and salbutamol on the return on investment in South African rands (ZAR), with ractopamine inclusion at 16% dietary crude protein (CP) as baseline. NC: negative control (no additives, 16% CP); ractopamine-16: 6 mg ractopamine/kg with 16% CP; ractopamine-13: 6 mg ractopamine/kg with 13% CP; salbutamol-6: 6 mg salbutamol/kg with 16% CP; salbutamol-4: 4 mg salbutamol/kg with 16% CP.

Discussion

The swine industry has made significant progress in nutritional technologies, which has led to a ca. 30% increase in the growth efficiency of pigs (Wu & Bazer, 2019; Kim *et al.*, 2024; Monteiro *et al.*, 2025). These significant advancements have provided a better understanding of how feeds are formulated, how feeding strategies are adopted, and the nutritional requirements of animals during any given phase (Pomar *et al.*, 2021). Similarly, higher consumer demands have arisen following these outcomes, resulting in increased preferences for affordable and high-quality pork that is healthy and free from residues (Costa *et al.*, 2018). In this regard, feed additives or feed supplements with carcass-modifying effects have become relevant. According to Kim *et al.* (2024), efficient utilisation of feed additives is necessary to increase the production efficiency of pigs and the profitability of pig production enterprises.

Feed additives are non-nutritive feed components that can enhance performance indices, increase feed utilisation efficiency, boost metabolism and health in animals, and preserve feeds (Abbas *et al.*, 2022). Ractopamine hydrochloride and salbutamol are beta-agonist feed additives with growth-promoting and carcass-modifying benefits, capable of meeting the modern consumers' demand for lean, tender, and high-quality pork with a low-fat content (Costa *et al.*, 2018). By stimulating beta-adrenergic receptors and the mTOR pathway (Ferreira *et al.*, 2017), ractopamine hydrochloride and salbutamol have been associated with altered nutrient partitioning, increased protein synthesis and muscular growth, reduced fat deposition, and enhanced feed efficiency (Hansen *et al.*, 1997; Mills *et al.*, 2002; Carr *et al.*, 2005; Bohrer *et al.*, 2013; Marcolla *et al.*, 2017; Panisson *et al.*, 2020; Abbas *et al.*, 2022). However, the high number of pigs that become fatigued and/or injured at packing plants as a direct consequence of ractopamine use is concerning (FDA, 2002; Ritter *et al.*, 2017), and safety and regulatory concerns persist regarding the use of ractopamine and salbutamol in pig and livestock nutrition. In some jurisdictions, such as China and the European Union, these concerns have led to the banning of beta-agonists in food-producing animals. These bans have been supported by reported cases of adverse health effects in humans following the consumption of products contaminated with beta-agonist residues, including food poisoning and cardiovascular or central nervous system disturbances (Cheng *et al.*, 2013; Mi *et al.*, 2014).

Salbutamol has been shown to accumulate more in edible organs such as the liver, kidneys, lungs, and intestines, rather than in muscle and fat tissues (Zhang *et al.*, 2017; Yang *et al.*, 2018). Sun *et al.* (2021) reported that, although residues in muscle and fat were undetectable or low after a seven-day withdrawal period, substantially higher concentrations persisted in edible organs. Similarly, ractopamine concentrations were reported to be higher in the lungs and kidneys than in muscle and fat tissues (Huang *et al.*, 2016). Given that edible offal and organ meats are commonly consumed in China and other regions, potential dietary exposure to beta-agonist residues may be elevated (Sun *et al.*, 2021). In addition, challenges associated with regulating illegal use and overdosing of beta-agonists further support the continued bans in these jurisdictions (Huang *et al.*, 2016).

Nevertheless, ractopamine is licensed by the FDA for use in finisher pigs during the last 28 to 42 days before slaughter (Davis & Belk, 2018). Moreover, both ractopamine and salbutamol are approved for use in the South African pig industry, with both supplements having no withdrawal periods when fed as feed additives to pigs following the manufacturers' prescribed inclusion levels (Needham *et al.*, 2017; Animate Animal Health, 2021). Qiang *et al.* (2007) supported the established zero-day withdrawal time set by the FDA in a residue depletion study of ractopamine and associated metabolites in the tissues, urine, and serum of pigs fed ractopamine-supplemented diets for 28 days. The study revealed that the concentrations of ractopamine in the edible tissues of the pigs following a zero-day withdrawal period were lower than the tolerance value established by the FDA and the MRL listed by the joint FAO/WHO Expert Committee on Food Additives. Furthermore, the ractopamine, salbutamol, and clenbuterol residue levels detected in fresh meat products (pork, beef, and lamb) in Jilin province in China were reportedly very low and the meat products were considered safe for human consumption (Xu *et al.*, 2019).

The beneficial role of beta-agonists as growth stimulants and carcass modifiers, particularly concerning sustainability and intensified animal production, cannot be overlooked (Abbas *et al.*, 2022), although their continued use in the modern pig with its high genetic potential for fast lean growth has been questioned. This study aimed to determine the efficacy of the beta-adrenergic agonists, ractopamine hydrochloride and salbutamol, as performance enhancers and carcass modifiers in the modern commercial pig, specifically Topigs Norsvin TN70. The study also aimed to ascertain whether lowering the CP concentration from the currently recommended 16% to 13%, while still meeting essential amino acid requirements, would impact the performance of finisher pigs fed supplemental ractopamine hydrochloride.

Results showed that ractopamine hydrochloride supplemented at 6 mg/kg feed did not affect the feed intake, ADG, or FCR of Topigs Norsvin TN70 finisher pigs, regardless of the total CP content of the feed. Other studies similarly found no effect on feed intake when ractopamine was included in the diet at 7.4 mg/kg (Gerlemann *et al.*, 2013; Ritter *et al.*, 2017) and 10 mg/kg (Needham *et al.*, 2017; Panisson *et al.*, 2020). In contrast, Armstrong *et al.* (2004) and Panisson *et al.* (2020) found an increase in the average daily feed intake when finisher pigs were fed a diet containing 5 mg ractopamine/kg. A decrease in the daily feed intake was noted by Herr *et al.* (2001), who supplemented ractopamine at a high dosage of 20 mg/kg, although others who used this same dosage reported no effect on intake (Armstrong *et al.*, 2004). The effect of ractopamine on average daily feed intake is thus not clear, but it appears that a dosage of 5–10 mg/kg generally has no effect on feed consumption in finisher pigs.

The positive effect of ractopamine use on the ADG of commercial finisher pigs has been well-established (Herr *et al.*, 2001; Armstrong *et al.*, 2004; See *et al.*, 2004; Gerlemann *et al.*, 2013; Needham *et al.*, 2017; Panisson *et al.*, 2020). Ractopamine is known to improve growth response by promoting protein deposition, inducing metabolic changes, and increasing muscle protein accretion by increasing the proportion of glycolytic muscle fibres, thereby allowing for the occurrence of enhanced muscle hypertrophy (Schinckel *et al.*, 2003; de Almeida *et al.*, 2012). Ractopamine activates protein kinase B, also known as Akt, which activates the mTOR pathway, thereby increasing muscle growth by stimulating protein synthesis (Ferreira *et al.*, 2017). Proteolysis is also reduced by ractopamine through the inhibition of the ubiquitin ligases, muscle atrophy F-box (MAFbx), and muscle RING finger (MuRF) (de Almeida *et al.*, 2012; Bodine *et al.*, 2014).

Additionally, beta-agonists utilise other pathways, such as the cAMP/PKA/CREB pathway, which also contributes to increased protein synthesis and muscle growth. In a recent study that lasted for 21 days, Reeves Pitts *et al.* (2023) observed that ractopamine supplementation at 20 mg/kg did not affect the feed intake or ADG, and thus feed efficiency, of unimproved Mangalica pigs. However, ractopamine hydrochloride supplementation might not always be effective, as Rickard *et al.* (2012) showed in a study in which PIC 337 barrows responded with only a numerical but not significant increase in ADG when fed a diet containing 7.4 mg ractopamine/kg.

As was observed for growth rate, feed efficiency was mostly improved in previous studies where ractopamine was included at various concentrations in the diets of finisher pigs. In the meta-analysis by Apple *et al.* (2007), it was noted that when significant effects on FCR were found, it was only up to an inclusion rate of 5 mg/kg, with further increases not providing any additional benefit. However, in a more recent study by Panisson *et al.* (2020), the FCR further improved as the ractopamine inclusion rate increased from 5 mg/kg to 10 mg/kg. In the current study, the FCR was not affected by ractopamine supplementation at 6 mg/kg at either 13% or 16% CP concentrations, despite gilts having slightly but significantly fatter carcasses at slaughter when fed the 13% CP diet, compared to the NC treatment.

In this study, salbutamol supplemented at 6 mg/kg depressed feed intake significantly, compared to pigs fed the NC and ractopamine-supplemented diets. Boars were less sensitive, with the 4 mg/kg salbutamol treatment only causing a numerical but not significant decrease in feed intake, whereas gilts' feed intakes were decreased by salbutamol supplementation at both inclusion rates. The lower feed intake of the 6 mg salbutamol/kg group resulted in a decreased growth rate in boars, but not in gilts, while the FCR was not affected. None of the growth parameters of the pigs that received 4 mg salbutamol/kg differed significantly from those of the NC pigs.

Beta-adrenergic agonists have been shown to suppress appetite in food-producing animals. There is evidence that salbutamol causes a dose-dependent decrease in feed intake by activating the central beta-adrenergic sites (Borsini *et al.*, 1982; Marchant-Forde *et al.*, 2012), as well as peripheral mechanisms affecting hunger and satiety signals, suggesting that salbutamol may cross the blood-brain barrier (Marchant-Forde *et al.*, 2012). Marchant-Forde *et al.* (2012) reported a significant decrease in feed consumption with the use of 8 mg salbutamol/kg in a finisher pig diet during the last four weeks before slaughter but did not find this decrease when supplementing salbutamol at 2 mg/kg or 4 mg/kg. Furthermore, Marchant-Forde *et al.* (2012) reported improved ADG values in commercial-type finisher pigs after four weeks of salbutamol supplementation at 2 mg/kg and 4 mg/kg, but not at 8 mg/kg, although feed efficiency was significantly improved by all three dosages. Fawcett *et al.* (2004) also reported that salbutamol had appetite-suppressant effects at higher dosages, when reductions in weight gain and feed intake were observed in male and female broiler chickens fed higher dietary levels of R-salbutamol.

In the present study, the appetite-suppressing effect of 6 mg salbutamol/kg led to a pronounced reduction in feed intake and a decline in growth rate. Gilts also experienced suppressed appetites at both 4 mg and 6 mg salbutamol/kg, without an effect on growth performance. The reason for this salbutamol × sex interaction is not clear but may be related to the anabolic effects of androgenic steroids such as testosterone in boars, which increase their protein deposition capacity, proportion of lean tissue, feed efficiency, and growth rate. Boars are therefore very reliant on a high supply of amino acids to sustain their high production potential (Xue *et al.*, 1997; Millet *et al.*, 2011; Dubois *et al.*, 2012; Elsbernd, 2014; Patience *et al.*, 2015). Gilts, in contrast, have slower growth, more subcutaneous fat, and increased intramuscular fat contents (Beattie *et al.*, 1999), and thus have lower requirements for dietary amino acids. As both sexes in this study received the same diets, amino acids were in oversupply for the gilts, and lower feed intakes consequently did not affect their growth.

The CP concentrations of the ractopamine-supplemented diets tested this study did not affect carcass weight, dressing percentage, or lean percentage. The lean percentage of gilt carcasses was, however, significantly lower for the 13% CP ractopamine-supplemented diet than for the NC, which contained 16% CP and no ractopamine. Ractopamine inclusion at 6 mg/kg in a feed containing 16% CP had no effect on the warm and cold carcass weights, dressing percentage, or lean percentage of the carcasses compared to the NC group. In the meta-analysis by Apple *et al.* (2007), it was shown that the lean percentage of carcasses mostly increased when 5 mg, 10 mg, and 20 mg ractopamine/kg was added to finisher diets, although some exceptions were reported. Gerlemann *et al.* (2013) similarly found that continuous dosing with 7.4 mg ractopamine/kg for 31 days before slaughter significantly decreased fat depth and increased lean percentage. In a more recent study by Soares *et al.* (2022), ractopamine supplemented at 20 mg/kg feed resulted in a significantly larger loin muscle area but did not affect the backfat thickness, as measured over the *longissimus thoracis* muscle, 6 cm lateral of the midline. Overall, the growth performance and carcass quality of the ractopamine-supplemented pigs in this study were not superior to those of the pigs fed the NC diet, with the ADG, FCR, average daily feed intake, hot carcass weight, cold carcass weight, and dressing percentage being comparable between the groups.

A previous study showed that ractopamine supplementation at 7.4 mg/kg feed increased the loin eye depth, but backfat depth was only reduced at the location of the tenth rib, and not at the first or last rib, suggesting that ractopamine may affect carcass composition differently at different sites on the carcass (Rickard *et al.*, 2017). March-Forde *et al.* (2012) noted the same effect for salbutamol at 2 mg/kg feed, with the loin muscle area increasing and backfat thickness at the tenth rib and last lumbar vertebra decreasing significantly, while the backfat thickness at the last rib was not affected. Furthermore, increasing the salbutamol dosage in the feed beyond 2 mg/kg did not result in any further effect. While the mechanisms of beta-agonists' effects on protein synthesis and muscle growth are well explained, their role in fat accretion is less conclusive and not fully understood (de Almeida *et al.*, 2012). Liu *et al.* (1994) reported that muscle tissue is more responsive than adipose tissue to beta-agonist supplementation, and its ability to reduce adipose accretion may depend on the potency of the agonist, its dose, and the treatment regimen. Salbutamol and other beta-agonists stimulate lipolysis, break down stored fat reserves, and inhibit lipogenesis, which involves the synthesis of new fat molecules (Mitchell, 2009). As a result, pigs supplemented with salbutamol exhibit reduced fat deposition and improved carcass composition, leading to a greater proportion of lean muscle tissue relative to fat tissue (Lu *et al.*, 2017). In the present study, gilts fed salbutamol-supplemented diets had significantly improved lean percentages and outperformed the ractopamine-supplemented groups. This enhanced performance suggests that salbutamol was able to elicit a significant effect on this carcass trait owing to its effect on lipolysis and muscle enhancement. Furthermore, supplementation with salbutamol resulted in significantly more carcasses falling within the P+O carcass class and fewer carcasses falling within the R+C class, compared to the carcasses of pigs that were in the NC and ractopamine-fed groups.

The PORCUS classification system used in South Africa favours leaner carcasses to meet the demands of the consumer, who is looking for healthier, leaner pork. Producers are paid a higher price per kilogram for a carcass with a P or O classification, which partially explains the better ROI (Figure 1) yielded by the treatment group that received the lower dose (4 mg/kg) of salbutamol. The lower feed consumption and subsequently lower feed cost also likely contributed to the higher ROI noted for pigs that were supplemented with 4 mg salbutamol/kg. The other treatment diets (NC, ractopamine-13, and salbutamol-6) also had higher ROI values than the ractopamine-16 group. Economic viability in pork production relies on complex interactions between feed costs, performance outcomes, market prices, and production efficiencies, and will likely vary for a different set of conditions to those prevalent during the current study.

Conclusions

The results of this study showed that ractopamine hydrochloride supplementation at 6 mg/kg did not affect the feed intake, ADG, or FCR of Topigs Norsvin TN70 boars and gilts, regardless of the total CP content of the feed. At 6 mg/kg, the ractopamine-supplemented diet containing 16% CP had no effect on the carcass indices of boars and gilts. However, the lean percentage of gilt carcasses was lower for the 13% CP ractopamine-supplemented diet, compared to the NC, which contained 16% CP and no ractopamine. It was also evident that the gilts' appetites were suppressed at lower salbutamol doses than the boars'. However, these decreases in feed intake resulted in decreased growth rates in boars but not in gilts, resulting in enhanced feed efficiency rates in gilts fed diets containing low doses of salbutamol. Gilts fed salbutamol-supplemented diets had carcasses with improved lean percentages, compared to the pigs that received ractopamine-supplemented diets. Dietary salbutamol supplementation also resulted in more carcasses that fell within the P+O carcass class and fewer in the R+C class, compared to the carcasses of pigs that were in the NC and ractopamine-supplemented groups.

It can thus be concluded that decreasing the CP concentration of ractopamine-supplemented diets from the recommended 16% to 13% has no effect on the growth indicators of either gilts or boars. However, supplementing ractopamine in a diet containing 13% CP has the potential to reduce the carcass lean percentage in gilts. Hence, the CP content of a diet containing ractopamine can be decreased from 16% to 13% for boars without any negative consequences, whereas gilts may still benefit from a higher dietary CP concentration, if the production of lean carcasses is a priority.

Considering the established safety of salbutamol use in pigs, the inclusion of salbutamol at 4 mg/kg has the potential to yield a higher ROI, when compared to ractopamine and non-supplemented diets. Further investigations into the economic benefits of salbutamol use in pigs are warranted.

Authors' contributions

This research was conducted to fulfil the requirements of an MSc (Agric) Animal Science degree for J.P.D.J., under the supervision of C.J.V.R. and in collaboration with W.J.S. C.J.V.R., W.J.S., and J.P.D.J. conceptualised and designed the experiment. J.P.D.J., W.J.S., R.J.C., and J.J.R.M.M. conducted the experiment. R.J.C. and J.J.R.M. analysed the data. E.A.A. and C.J.V.R. wrote the draft manuscript. E.A.A., C.J.V.R., and W.J.S. revised, corrected, and edited the manuscript before submission.

Conflict of interest declaration

The authors have no conflicts of interest to declare.

References

Abbas, K., Raza, A., Vasquez, R.D., Roldan, M.J.M., Malhotra, N., Huang, J.C., Buenafe, O.E.M., Chen, K.H.-C., Liang, S.-S., & Hsiao, C.-D., 2022. Ractopamine at the center of decades-long scientific and legal disputes: A lesson on benefits, safety issues, and conflicts. *Biomolecules*, 12:1342. DOI: https://doi.org/10.3390/biom12101342

Åkerfeldt, M.P., Lindberg, J.E., Göransson, L., & Andersson, K., 2019. Effects of reducing dietary content of crude protein and indispensable amino acids on performance and carcass traits of single-phase- and 2-phase-fed growing-finishing pigs. *Livestock Science*, 224:96–101. DOI: https://doi.org/10.1016/j.livsci.2019.04.014

Alfredo, M.M.N., Rodrigo, H.M.M.G., Amarylis, C.B.A.W., & Alessandro, G.S., 2017. The challenges of ractopamine use in meat production for export to European Union and Russia. *Food Control*, 72: 289–292. DOI: https://doi.org/10.1016/j.foodcont.2015.10.015

Andretta, I., da Silva, M.K., Lehnen, C.R., Demori, A.B., Remus, A., & Lovatto, P.A., 2012. Meta-analysis of the relationship between ractopamine and dietary lysine levels on carcass characteristics in pigs. *Livestock Science,* 143:91–96. DOI: https://doi.org/10.1016/j.livsci.2011.09.004

Animate Animal Health, 2021. Salbutamate®10%. Pigs. Available: https://www.salbutamate.com/pigs/

Apple, J.K., Rincker, P.J., Mckeith, F.K., Carr, S.N., Armstrong, T.A, & Matzat, P.D., 2007. Review: Meta-analysis of the ractopamine response in finishing swine. *The Professional Animal Scientist,* 23:179–196. DOI: https://doi.org/10.15232/S1080-7446(15)30964-5

Armstrong, T.A., Ivers, D.J., Wagner, J.R., Anderson, D.B., Weldon, W.C., & Berg, E.P., 2004. The effect of dietary ractopamine concentration and duration of feeding on growth performance, carcass characteristics, and meat quality of finishing pigs. *Journal of Animal Science*, 82:3245–3253. DOI: https://doi.org/10.2527/2004.82113245x

Arp, T.S., Howard, S.T., Woerner, D.R., Scanga, J.A., McKenna, D.R., Kolath, W.H., Chapman, P.L., Tatum, J.D., & Belk, K.E., 2014. Effects of dietary ractopamine hydrochloride and zilpaterol hydrochloride supplementation on performance, carcass traits, and carcass cutability in beef steers. *Journal of Animal Science,* 92:836–843. DOI: https://doi.org/10.2527/jas.2013-7122

Beattie, V.E., Weatherup, R.N., Moss, B.W., & Walker, N., 1999. The effect of increasing carcass weight of finishing boars and gilts on joint composition and meat quality. *Meat Science,* 52:205–211. DOI: https://doi.org/10.1016/S0309-1740(98)00169-7

Bodine, S.C. & Baehr, L.M., 2014. Skeletal muscle atrophy and the E3 ubiquitin ligases MuRF1 and MAFbx/atrogin-1. *American Journal of Physiology-Endocrinology and Metabolism*, 307:E469–484. DOI: https://doi.org/10.1152/ajpendo.00204.2014

Bohrer, B.M., Kyle J.M., Boler D.D., Rincker P.J., Ritter, M.J., & Carr, S.N., 2013. Meta-analysis of the effects of ractopamine hydrochloride on carcass cutability and prima yields of finishing pigs. *Journal of Animal Science*, 91:1015–1023. DOI: https://doi.org/10.2527/jas.2012-5647

Borsini, F., Bendotti, C., Thurlby, P., & Samanin, R., 1982. Evidence that systemically administered salbutamol reduces food intake in rats by acting on central beta-adrenergic sites. *Life Sciences*, 30:905–911. DOI: https://doi.org/10.1016/0024-3205(82)90618-X

Carr, S.N., Iver, D.J., Anderson, D.B., Jones, D.J., Mowrey, D.T., England, M.B., Killefer, J., Rincker, P.J., & McKeith, F.K., 2005. The effects of ractopamine hydrochloride on lean carcass yields and pork quality characteristics. *Journal of Animal Science*, 83:2886–2893. DOI: https://doi.org/10.2527/2005-83122886x

Centner, T., Alvey, J.C., & Stelzleni, A.M., 2014. Beta agonists in livestock feed: status, health, concerns, and international trade. *Journal of Animal Science*, 92:4234–4240. DOI: https://doi.org/10.2527/jas.2014-7932

Cheng, J., Wang, S., & Su, X.O., 2013. Simultaneous Identification and quantification of 20 β-receptor agonists in feed using gas chromatography-tandem mass spectrometry. *PloS one,* 8(10):e76400. DOI: https://doi.org/10.1371/journal.pone.0076400

Costa, O.A.D., Feddern, V., Athayde, N.B., Manzke, N.E., Roça, R.D.O., Lopes, L.D.S., & De Lima, G.J.M.M., 2018. Ractopamine supplementation improves leanness and carcass yield, minimally affecting pork quality in immunocastrated pigs. *Scientia Agricola*, 75:197–207. DOI: https://doi.org/10.1590/1678-992X-016-0321

Davis, H. & Belk, E., 2018. Managing meat exports considering production technology challenges. *Animal Frontiers*, 8:23–29. DOI: https://doi.org/10.1093/af/vfy007

De Almeida, V.V., Nuñez, A.J.C., & Miyada, V.S., 2012. Ractopamine as a metabolic modifier feed additive for finishing pigs: A review. *Brazilian Archives of Biology and Technology*, 55:445–456. DOI: https://doi.org/doi.org/10.1590/S1516-89132012000300016

De Klerk, M.J., 2016. The effect of r-salbutamol on apparent digestibility, feed efficiency, growth, carcass characteristics, and meat quality of feedlot lambs. MSc (Agric) thesis. Stellenbosch University, South Africa.

Du Toit, R., 2017. The influence of R-salbutamol on feedlot performance, carcass characteristics and meat quality in Dorper ram, wether and ewe lambs. MSc (Agric) thesis. Stellenbosch University, South Africa.

Dubois, V., Laurent, M., Boonen, S., Vanderschueren, D., & Claessens, F., 2012. Androgens and skeletal muscle: cellular and molecular action mechanisms underlying the anabolic actions. *Cell and Molecular Life Sciences,* 69:1651–1667. DOI: https://doi.org/10.1007/s00018-011-0883-3

Elanco, 2023. Paylean™ (ractopamine hydrochloride). Swine product directory. Available: https://farmanimal.elanco.com/za/product-directory-swine

Elsbernd, A.J.O., 2014. Nutrient utilization, pork quality, and lysine requirement of immunological castrates. MSc (Animal Science) thesis. Iowa State University, Ames, Iowa, United States.

FAO, 2012. Food and Agriculture Organization of the United Nations. Fact sheet on Codex work on ractopamine. Available: https://www.fao.org/fileadmin/user_upload/agns/pdf/Ractopamine_info_sheet_Codex-JECFA_rev_26April2012__2_.pdf [22 October 2025].

Fawcett, J.P., Ravindran, V., Morel, P.C.H., Zhang, M., Ciofalo, V.B., Spainhour, C.B., & Aberg, G., 2004. Influence of salbutamol administered as the single active enantiomer (R-salbutamol) on the growth performance and carcass characteristics of broiler chickens. *Animal Science*, 78:23–30. DOI: https://doi.org/10.1017/S1357729800053807

FDA, 1999. Freedom of information summary: Original new animal drug application - Paylean. Retrieved October 20, 2025, from Food and Drug Administration.

FDA, 2002. Freedom of information summary: Supplemental new animal drug application. NADA 140 863, Ractopamine hydrochloride (Paylean). Available: https://animaldrugsatfda.fda.gov/adafda/app/search/public/document/downloadFoi/508 [11 June 2025].

FDA, 2006. New Animal Drugs for Use in Animal Feeds; Ractopamine. Department of Health and Human Services, Food and Drug Administration, 21 CFR Part 558. Federal Register / Vol. 71, No. 224 / Tuesday, November 21, 2006 / Rules and Regulations. Available: https://www.govinfo.gov/content/pkg/FR-2006-11-21/pdf/E6-19615.pdf [11 June 2025].

Ferreira, M.S.S., Araújo, T.S., Alves, A.C., Porto, L.C.J., Schinckel, A.P., Rambo, Z.J., & Sousa, R.V., 2017. Ractopamine with dietary lysine concentrations above basal requirements of finishing barrows improves growth performance, carcass traits and modifies the mTor signalling pathway. *Animal Production Science,* 57:1682–1691. DOI: https://doi.org/10.1071/AN15565

Gerlemann, G.D., Allee, G.L., Boler, D.D., Ritter, M.J., Pierdon, M.K., & Carr, S.N., 2013. The effects of ractopamine hydrochloride feeding programs on growth and carcasses of finishing pigs marketed in 2 different groups. *The Professional Animal Scientist*, 29:271–277. DOI: https://doi.org/10.15232/S1080-7446(15)30233-3

Halsey, C.H.C., Weber, P.S., Reiter, S.S., Stronach, B.N., Bartosh, J.L., & Bergen, W.G., 2011. The effect of ractopamine hydrochloride on gene expression in adipose tissues of finishing pigs. *Journal of Animal Science*, 89:1011–1019. DOI: https://doi.org/10.2527/jas.2010-3269

Hansen, J.A., Yen, J.T., Nelssen, J.L., Nienaber, J.A., Goodband, R.D., & Wheeler, T.L., 1997. Effects of somatotropin and salbutamol in three genotypes of finishing barrows: growth, carcass and calorimeter criteria. *Journal of Animal Science*, 75:1798–1809. DOI: https://doi.org/10.2527/1997.7571798x

Herr, C.T., Hankins, S.L., Schinckel, A.P., & Rickert, B.T., 2001. Evaluation of three genetic populations of pigs for response to increasing levels of ractopamine. Purdue University Pork Page Archive. Available: https://www.ansc.purdue.edu/pork-archive/pubs/EvalGeneticPopPaylean.pdf

Huang, L., Shi, J., Pan, Y., Wang, L., Chen, D., Xie, S., Liu, Z., & Yuan, Z., 2016. Elimination and concentration correlations between edible tissues and biological fluids and hair of ractopamine in pigs and goats fed with ractopamine-medicated feed. *Journal of Agricultural and Food Chemistry,* 64:2012–2020. DOI: https://doi.org/10.1021/acs.jafc.6b00456.

Juarez, M.E., Carlin, S.C., Rebollo, F., Verdugo-Rodriguez, A., & Martinez-Gomez, D., 2016. Sensory evaluation of cooked pork meat (*M. bicepsfemoris*) fed with and without ractopamine hydrochloride associated to age but not gender of the non-trained panelist. *The Journal of Animal & Plant Sciences*, 26(1):40–45.

Kim, S.W., Deng, Z., & Choi. H., 2024. Advances of nutritional technologies and science in pig production. *Animal Industry and Technology*, 11:45–55. DOI: https://doi.org/10.5187/ait.2024.11.1.45

Liu, C.Y., Grant, A.L., Kim, K.H., Ji, S.Q., Hancock, D.L., Anderson, D.B., & Mills, S.E., 1994. Limitations of ractopamine to affect adipose tissue metabolism in swine. *Journal of Animal Science,* 72:62–67. DOI: https://doi.org/10.2527/1994.72162x

Lu, H., Zhang, H., Zhu, T., Xiao, Y., Xie, S., Gu, H., Cui, M., & Luo, L., 2017. Metabolic effects of clenbuterol and salbutamol on pork meat studied using internal extractive electrospray ionization mass spectrometry. *Scientific Reports*, 7:5136. DOI: https://doi.org/10.1038/s41598-017-05496-6

Marchant-Forde, J.N., Lay Jr., D.C., Marchant-Forde, R.M., McMunn, K.A., & Richert, B.T., 2008. The effects of R-salbutamol on behavior and physiology of finishing pigs. *Journal of Animal Science*, 86:3110–3124. DOI: https://doi.org/10.2527/jas.2008-1075

Marchant-Forde, J.N., Lay, D.C., Marchant-Forde, R.M., McMunn, K.A., & Richert, B.T., 2012. The effects of R-salbutamol on growth, carcass measures, and health of finishing pigs. *Journal of Animal Science*, 90:4081–4089. DOI: https://doi.org/10.2527/jas.2011-4423

Marchant-Forde, J.N., Lay, D.C., Pajor, E.A., Richert, B.T. & Schinckel, A.P., 2003. The effects of ractopamine on the behavior and physiology of finishing pigs. *Journal of Animal Science*, 81:416–422. DOI: 10.2527/2003.812416x

Marcolla, C.S., Holanda, D.M., Ferreira, S.V., Rocha, G.C., Serão, N.V.L., Duarte, M.S., Abreu, M.L.T., Saraiva, A., 2017. Chromium, CLA, and ractopamine for finishing pigs. *Journal of Animal Science,* 95:4472–4480. DOI: https://doi.org/10.2527/jas2017.175

Martins, D.D.S., Soares, M.A., & Steffens, J., 2015. Carcass quality and yield of pork cuts with ractopamine use. *Ciência Rural*, 45:1503–1508. DOI: https://doi.org/10.10.1590/0103-8478cr20140625

Mi, J., Li, S., Xu, H., Liang, W., & Sun, T., 2014. Rapid analysis of three β-agonist residues in food of animal origin by automated on-line solid phase extraction coupled to liquid chromatography and tandem mass spectrometry. *Journal of Separation Science*, 37:2431–2438. DOI: https://doi:10.1002/jssc.201400442

Millet, S., Gielkens, K., de Brabander, D., & Janssens, G.J., 2011. Considerations on the performance of immunocastrated male pigs. *Animal*, 5:1119–1123. DOI: https://doi.org/10.1017/S1751731111000140

Mills, S.E., 2002. Biological basis of the ractopamine response. *Journal of Animal Science,* 80(E-suppl_2):E28–E32. DOI: https://doi.org/10.2527/animalsci2002.80E-Suppl 2E28x

Mitchell, A.D., 2009. Effect of ractopamine on growth and body composition of pigs during compensatory growth. *Animal*, 3:173–180. DOI: https://doi.org/10.1017/S1751731108003285

Monteiro, M.S., Carnevale, R.F., Muro, B.B.D., Mezzina, A.L.B., Carnino, B.B., Poor, A.P., Matajira, C.E.C., & Garbossa, C.A.P., 2025. The role of nutrition across production stages to improve sow longevity. *Animal*, 15:189. DOI: https://doi.org/10.3390/ani15020189

Needham, T., Hoffman, L.C., & Gous, R.M., 2017. Growth responses of entire and immunocastrated male pigs to dietary protein with and without ractopamine hydrochloride. *Animal,* 11:1482–1487. DOI: https://doi.org/10.1017/S1751731117000271

Pacelle, W., 2014. Banned in 160 nations, why is ractopamine in US Pork (Op-Ed). Live Science. Expert Voices: Op-Ed & Insights. Available: https://www. livescience.com/47032-time-for-us-to-ban-ractopamine.html

Panisson, J.C., Maiorka, A., Oliveira, S.G., Saraiva, A., Duarte, M.S., Silva, K.F., Santos, E.V., Tolentino, R.L.S., Lopes, I.M.G., Guedes, L.L.M., & Silva, B.A.N., 2020. Effect of ractopamine and conjugated linoleic acid on performance of late finishing pigs. *Animal*, 14:277–284. DOI: https://doi.org/10.1017/S1751731119001708

Park, J., Campbell, C.P., Squires, E.J., de Lange, C.F.M., & Mandell, I.B., 2019. Effects of pig genotype, immunological castration, and use of ractopamine on growth performance, carcass traits, and pork quality for entire male pigs. *Canadian Journal of Animal Science,* 99:82–106. DOI: https://doi.org/10.1139/cjas-2017-0166

Patience, J.F., Rossoni-Serão, M.C., & Gutiérrez, N.A., 2015. A review of feed efficiency in swine: Biology and application. *Journal of Animal Science and Biotechnology*, 6:1–9. DOI: https://doi.org/10.1186/s40140-015-0031-2

Poletto, R., Meisel, R.L., Richert, B.T., Cheng, H.W., & Marchant-Forde, J.N., 2010. Behavior and peripheral amine concentrations in relation to ractopamine feeding, sex, and social rank of finishing pigs. *Journal of Animal Science*, 88:1184–1194. DOI: https://doi.org/10.2527/jas.2008-1576

Pomar, C., Andretta, I., & Remus, A., 2021. Nutrient losses. Feeding strategies to reduce nutrient losses and improve the sustainability of growing pigs. *Frontiers in Veterinary Science*, 8:742220. DOI: https://doi.org/10.3389/fvets.2021.742220

Qiang, Z., Shentu, F., Wang, J., Chang, J., & Shen, J., 2007. Residue depletion of ractopamine and its metabolites in swine tissues, urine and serum. *Journal of Agricultural and Food Chemistry*, 55:4319–4326. DOI: https://doi.org/10.1021/jf070167c

Reeves Pitts, M.A., Smith, H.R., Amerson, E.C., Starkey, J.D., Starkey, C.W., Sawyer, J.T. & Brandebourg, T.D., 2023. Feeding ractopamine improves the growth performance and carcass characteristics of the lard-type Mangalica pig. *Animal (Basel)*, 13:3857. DOI: https://doi.org/10.3390/ani13243857

Rickard, J.W., Allee, G.L., Rincker, P.J., Gooding, J.P., Acheson, R.J., McKenna, D.R., Puls, C.L., & Carr, S.N., 2017. Effects of ractopamine hydrochloride on the growth performance and carcass characteristics of heavy-weight finishing pigs sent for slaughter using a 3-phase marketing strategy. *Translational Animal Science*, 1:406–411. DOI: https://doi.org/10.2527/tas2017.0053

Rickard, J.W., Wiegand, B.R., Pompeu, D., Hinson, R.B., Gerlemann, G.D., Disselhorst, R., & Allee, G.L., 2012. The effect of corn distiller's dried grains with solubles, ractopamine, and conjugated linoleic acid on the carcass performance, meat quality, and shelf-life characteristics of fresh pork following three different storage methods. *Meat Science*, 90:643–652. DOI: https://doi.org10.1016/j.meatsci.2011.10.007

Ritter, M.J., Johnson, A.K., Benjamin, M.E., Carr, S.N., Ellis M., Faucitano, L., Grandin, T., Salak-Johnson, J.L., Thomson, D.U., Goldhawk, C., & Calvo-Lorenzo, M.S., 2017. Effects of ractopamine hydrochloride (Paylean) on welfare indicators for market weight pigs. *Translational Animal Science*, 1:533–558. DOI: https://doi.org/10.2527/tas2017.0060

Rocha, G.C., Duarte, M.E., & Kim, S.W., 2022. Advances, implications, and limitations of low-crude- protein diets in pig production. *Animal*, 12:3478. DOI: https://doi.org/10.3390/ani12243478

Samuels, M.L., 1989. Statistics for life sciences. Collier MacMillan Publishing, London. pp. 505.

SAS, 2021. Statistical Analysis Systems user's guide. SAS Institute Inc., Cary, North Carolina, USA.

SAS, 2023. Statistical Analysis Systems user's guide. SAS Institute Inc., Cary, North Carolina, USA.

Schinckel, A.P., Li, N., Richert, B.T., Preckel, P.V., & Einstein, M.E., 2003. Development of a model to describe the compositional growth and dietary lysine requirements of pigs fed ractopamine. *Journal of Animal Science*, 81:1106. DOI: https://doi.org/2527/2003.8151106x

See, M.T., Armstrong, T.A., & Weldon, W.C., 2004. Effect of a ractopamine feeding program on growth performance and carcass composition in finishing pigs. *Journal of Animal Science*, 82:2474–2480. DOI: https://doi.org/10.2527/2004.8282474

Soares, M.H., Júnior, D.T.V., de Amorim Rodrigues, G., Júnior, R.L.C., Rocha, G.C., Bohrer, B.M., Juárez, M., de Souza Duarte, M., & Saraiva, A., 2022. Effects of feeding ractopamine hydrochloride with or without supplemental betaine on live performance, carcass and meat quality traits, and gene expression of finishing pigs. *Meat Science*, 191:108851. DOI: https://doi.org/10.1016/j.meatsci.2022.108851

Soji, Z., Chikwanda, D., Chikwanda, A.T., Jaja, I.F., Mushonga, B., & Muchenje, V., 2015. Relevance of the formal red meat classification system to the South African informal livestock sector. *South African Journal of Animal Science*, 45:263–277. DOI: https://doi.org/10.4314/sajas.v45i3.5

Steyn, W.J., Casey, N.H., & van Rensburg, J.C., 2012. Effects of different penning conditions, feeding regimens and season on growth and carcass attributes of boars of a selected genetic line. *South African Journal of Animal Science*, 42:2. DOI: http://dx.org/10.4314/sjas-v42i2.11

Sun, L., Zhu, M., Shi, J., Mi, K., Ma, W., Xu, X., Wang, H., Pan, Y., Tao, Y., Liu, Z., & Huang, L., 2021. Excretion and residual concentration correlations of salbutamol between edible tissues and living samples in pigs and goats. *Frontiers in Pharmacology*, 21:754876, DOI: https://doi.org/10.10.3389/fphar.2021.754876

Visser, D.P., 2004. Structuring of breeding objectives in the pork supply chain in South Africa. PhD (Agric) thesis. University of Pretoria, South Africa.

Webb, E., Allen, J., & Morris, S., 2018. Effects of non-steroidal growth implant and dietary zilpaterol hydrochloride on growth and carcass characteristics of feedlot lambs. *South African Journal of Animal Science*, 48(4):601–608. DOI: http://dx.org/10.4314/sajas.v48i4.1

Webb, E.C., Stock, C., & Morris, S.D., 2023. Comparison between the effects of zilpaterol hydrochloride and R-salbutamol fed during the finishing period on the growth and carcass characteristics of feedlot cattle. *South African Journal of Animal Science*, 53:5. DOI: https://doi.org/10.4314/sajas.v53i5.01

Wu, G. & Bazer, F.W., 2019. Application of new biotechnologies for improvements in swine nutrition and pork production. *Journal of Animal Science and Biotechnology*, 10:28. DOI: https://doi.org/10.1186/s40104-019-0337-6

Xu, C., Gao, H., Pan, N., Jiang, M., Huang, Y., Zhu, K., Gong, P., & Lv, S., 2019. Clenbuterol, salbutamol, and ractopamine in fresh meat products in Jilin province, China. *International Journal of Food Properties*, 22:1183–1194. DOI: https://doi.org/10.1080/10942912.2019.1634100

Xue, J.L., Dial, G.D., & Pettigrew, J.E., 1997. Performance, carcass, and meat quality advantages of boars over barrows: A literature review. *Swine Health and Production,* 5:1

Yang, Y., Gu, X., Dong, Y., Li, J., Ni, H., Xue, M., Zhao, Z.., Sun, Z., & Qin, Y., 2018. Determination of salbutamol residues in goat various tissues after exposure to growth-promoting doses. *Journal of Analytical Toxicology*, 42:55–62. DOI: https://doi:10.1093/jat/bkx073

Zaitseva, N.V., Shur, P.Z., Atiskova, N.G., Kiryanov, D.A., & Kamaltd, M.R., 2014. Health risk assessment of exposure of ractopamine through consumption of meat products. *International Journal of Advanced Research*, 2:538–545.

Zhang, K., Tang, C., Meng, Q., Du, W., Bo, T., Zhao, Q., Liang, X., Liu, S., Zhang, Z., & Zhang, J., 2017. Residues of salbutamol and identification of its metabolites in beef cattle. *Journal of Agricultural and Food Chemistry*, 65:2867–2875. DOI: https://doi.org/10.1021/acs.jafc.7b00189