



OPEN Identifying slow-growing commercial pigs using growth performance and health indicators

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This study aimed to evaluate the growth performance and health status of commercial pigs in different body weight (BW) groups and develop methods for identifying slow-growing pigs. The research observed 79 commercial pigs grouped from 104 to 202 days of age, collecting data on BW, feed intake, and body condition score (BCS) from caliper. Results showed that BCS were highly correlated with BW ($r > 0.85$, $P < 0.001$), providing a simple method for assessing commercial pig BW. Commercial pigs with slaughter BWs below 114 kg at approximately 200 days old were identified as slow-growing individuals. White blood cell count, insulin-like growth factor binding protein-3, and blood urea nitrogen were identified as potential biomarkers for identifying slow-growing pigs. Economic analysis revealed that profitability across all BW groups was highly sensitive to market conditions, with feed costs being the most significant factor. Low BW groups performed better in low-price markets but reach break-even points later under medium to high-price scenarios.

Background

In China, large-scale commercial pig farms typically employ an all-in/all-out production system. While this system can reduce disease transmission, improve management efficiency, and enhance production performance, it is inherently designed for pigs with average body conditions¹. However, individual variations in growth performance exist among pigs within the same batch, with approximately 10–15% of pigs exhibiting slow growth. These slow-growing pigs are often sold at discounted prices or require extended periods to reach suitable slaughter body weight (BW), thereby affecting farm turnover rates and economic benefits^{2,3}. Consequently, identifying and managing slow-growing pigs is crucial for improving production efficiency and avoiding economic losses.

In production practice, BW is a particularly accessible and reliable performance-related indicator. Compared to other indicators, BW measurement is generally more direct, objective, and suitable for large-scale production environments. A good understanding of commercial pigs' BW is essential for optimizing management, improving performance, and enhancing profitability⁴. However, direct weighing is not only labor-intensive but may also lead to changes in pigs' feeding behavior, induce stress responses, cause BW loss, and even jeopardize health^{5,6}. Indirect weighing methods, such as measuring body length, heart girth, and height, or using image analysis and machine vision technologies, while feasible, are often limited in practical application due to equipment costs and technical complexity^{7,8}. In practice, most farmers adopt the visual observation to estimate the BW of commercial pigs, and the accuracy relies on their experience.

Hematological and biochemical indicators can reflect the nutritional and health status of pigs⁹. Improvements in immunoglobulin and lymphocytes secretion¹⁰, imbalances in the oxidation-antioxidation system¹¹, decreases in insulin-like growth factor-1 (IGF-1), insulin, leptin, and amino acid concentrations³, as well as factors such as sub-clinical infection¹², stress¹³, immunosuppression¹⁴, and intestinal barrier damage¹⁵ may all be associated with slow growth in commercial pigs.

Scientific studies on pig performance in real farm conditions are scarce. Our research, conducted in a large-scale commercial farm, addresses this gap, offering insights directly applicable to industry practices. The present study aimed

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to: (1) evaluate the applicability of caliper measurements as a non-invasive method for BW estimation in commercial pigs; (2) assess the growth performance and hematological indicators of growing pigs with different growth rates at different ages; (3) establish the thresholds for the slow-growing pigs during the grower-finisher stage; and (4) screen and evaluate the indicators of slow-growing pigs.

Methods

This study was conducted on a commercial pig farm located in Shandong province. The pig farm was designed with a capacity for 8,000 fattening pigs, spread across eight barns. Each house was scaled to house 800 to 1,000 fattening pigs. The house utilized in this study were specially equipped with 40 pig measurement systems (Osborne Industries, Inc., Osborne, KS, USA), capable of accurately determining the daily feed intake and daily weight gain of each pig. The collection of all the clinical samples was approved by the Dezhou Animal Ethics Committee (DAEC 132/2022). All animal experiments were conducted in strict accordance with the ARRIVE guidelines, and were reported following the relevant guidelines and regulations of the National Institutes of Health.

Housing and management of the farm

There were 34 pens in a house and the floor was made up of 2/3 concrete grids. Each pen (13 pigs) had a single-space FIRE feeder (Osborne Industries Inc., Osborne, KS, USA). Each FIRE feeder was equipped with a weighing scale (ACCU-ARM Weigh Race, Osborne Industries, Inc., Osborne, KS, USA) to measure the BW of the pigs using the feeder. The fattening facilities were provided with the automatic feeding, environmental control and mechanical ventilation system (climate controller for controlling fans of different sizes).

Throughout the whole fattening stage, the pigs were provided with routine prevention procedures and permanent veterinary care. The pigs aged 56 and 84 days were vaccinated against pseudorabies and classic swine fever. Diets were formulated to approximately meet or exceed the nutrient requirements of growing pigs as suggested by NRC 2012 (Table 1)¹⁶. The pigs had free access to the feeders and four nipple drinkers.

Experimental design

A total of 79 pigs aged 104 days (41 females and 38 males (castrated)); (Large White × Landrace) × Duroc were allocated into three groups as High BW (Abbreviated as H, 27 pigs, $42.5 \text{ kg} \leq \text{BW} \leq 55.1 \text{ kg}$), Medium BW (Abbreviated as M, 25 pigs, $32.6 \text{ kg} \leq \text{BW} \leq 42.4 \text{ kg}$) and Low BW (Abbreviated as L, 27 pigs, $18.9 \text{ kg} \leq \text{BW} \leq 32.5 \text{ kg}$) group¹⁷. Feed intake, feeder occupation time, BW, and animal identity were recorded every time when a pig visited the feeder from 104 to 202 days old. The BW for 24 and 70 days old were obtained through precise individual weighing methods. Specifically, at 24 days old, each pig individually was weighed using an electronic scale (DELIXI Electric Co., Ltd., Wenzhou, China) while applying conventional ear tags. Similarly, at 70 days old, those pigs were weighed again using an electronic platform scale (DELIXI Electric Co., Ltd., Wenzhou, China) during the process of installing radio frequency identification (RFID) electronic ear tags. To understand the background of mixed infection in these pigs, at the start of the study, porcine circovirus 2 (PCV2), porcine circovirus 3 (PCV3), porcine reproductive and respiratory syndrome virus (PRRSV), pseudorabies virus glycoprotein E (PRV-gE), classical swine fever virus (CSFV), porcine epidemic diarrhea virus (PEDV), rotavirus (RV) and lawsonia intracellularis (LI) were detected using the real-time PCR. The testing method was consistent with previous reports¹⁸, with a cycle threshold value ≤ 40 considered positive. The primers for the pathogens were detailed in Supplementary Material Table S1.

Records

Clinical scores

A clinical score (CS) was assigned based on the mental, tear straining, fur and clinical status of the commercial pig to quantitatively evaluate its overall health status. The standards were adapted from the sow body condition scoring¹⁹:

- 5-In good shape, no sign of tear staining, shiny fur and activity.
- 4-In good shape, slight tear straining and rough fur.
- 3-Slightly thin, obvious tear straining, rough and slightly dirty fur.
- 2-Thin, serious tear straining, rough and dirty fur and depression/coughing/diarrhea.
- 1-Severely thin with visible spinal bones, weakness and illness.

Body condition scores

A body condition caliper (Continuous numbers with a range of 0–30 cm) was used for body condition score (BCS) when pigs were 112, 180 and 202 days old. First, the pig was restrained with a hog strainer and the body was kept straight. Next, the last rib of the pig was located. The spine was then touched with the hand, the caliper was placed at the center of the spine and gently closed to make the two points touch the skin. Finally, the number of caliper was recorded.

Growth performance indicators

Growth performance was determined by assessing BW, average daily gain (ADG), average daily feed intake (ADFI) and feed conversion ratio (FCR) for each group at 112, 152, 180 and 202 days old. The following calculation formulae were used:

$$\text{ADG} = (\text{end weight} - \text{initial weight}) / \text{test days}$$

$$\text{ADFI} = \text{total feed intake} / \text{test days}$$

$$\text{FCR} = \text{feed consumed} / \text{body weight gain}$$

	Diets		
	71–118 d	119–155 d	156–220 d
Ingredients, %			
Maize	51.316	53.145	51.884
Soybean meal 43	13.340	11.933	9.647
Wheat	23.000	23.000	27.000
Rice bran	8.000	8.000	8.000
Calcium carbonate	1.296	1.159	1.101
Calcium hydrogen phosphate III	0.857	0.873	0.715
L-lysine monohydrochloride (98.5%)	0.600	0.574	0.554
Soybean oil	0.447	0.207	0.055
Sodium chloride (98.5%)	0.360	0.360	0.360
Trace mineral and vitamin mixture*	0.230	0.230	0.205
L-Threonine (98.5%)	0.192	0.188	0.185
DL-Methionine(98.5%)	0.173	0.153	0.132
L-Threonine (25%)	0.159	0.149	0.132
Xylanase	0.020	0.020	0.020
Phytase	0.010	0.010	0.010
Composition			
Dry matter, %	86.28	86.19	86.17
Moisture, %	13.72	13.81	13.83
Ash, %	4.73	4.55	4.32
Crude protein, %	15.50	15.00	14.50
Ether extract, %	3.89	3.69	3.62
Crude fiber, %	2.66	2.61	2.62
Neutral detergent fiber, %	7.91	7.89	8.28
Acid detergent fiber, %	3.19	3.14	3.17
Lys, %	1.16	1.11	1.05
C18:2, %	1.71	1.60	1.56
Ca, %	0.70	0.65	0.60
P-total, %	0.62	0.62	0.59
K, %	0.66	0.63	0.61
Na, %	0.15	0.15	0.15
Cl, %	0.39	0.38	0.38
Zn, mg	28.35	27.94	29.02
Cu, mg	4.66	4.50	4.57
Dietary electrolyte balance, meq	123.91	118.74	112.85
ATTD-P-s, %	0.25	0.25	0.22
STTD-P-s, %	0.30	0.30	0.28
Salt, %	0.35	0.35	0.35
Ca/P-total	1.13	1.06	1.02
Choline, mg	1090.17	1062.19	990.50
ME-g/f, Kcal	3229	3220	3213
DE-g/f, Kcal	3352	3340	3330
NE-g/f, Kcal	2470	2470	2470
SID Lys-s/NE-piglet/g/f, g/Mcal	4.25	4.05	3.85
SID Lys-s, %	1.05	1.00	0.95
SID Met-s, %	0.39	0.36	0.34
SID Cys-s, %	0.22	0.22	0.21
SID M + C-s, %	0.61	0.58	0.55
SID Thr-s, %	0.63	0.61	0.59
SID Trp-s, %	0.18	0.17	0.16
SID Ile-s, %	0.49	0.47	0.44
SID Arg-s, %	0.87	0.83	0.80
SID Leu-s, %	1.08	1.06	1.01
SID Val-s, %	0.61	0.59	0.57
DigMet/DigLys-s	0.37	0.36	0.36
Continued			

	Diets		
	71–118 d	119–155 d	156–220 d
DigCys/DigLys-s	0.21	0.22	0.22
DigThr/DigLys-s	0.60	0.61	0.62
DigTrp/DigLys-s	0.17	0.17	0.17
DigArg/DigLys-s	0.83	0.83	0.84
DigIle/DigLys-s	0.46	0.47	0.47
DigVal/DigLys-s	0.58	0.59	0.60
DigLeu/DigLys-s	1.03	1.06	1.07
DigMet + Cys/DigLys-s	0.58	0.58	0.58

Table 1. Ingredient and nutrient composition of diets for commercial pigs at different growth stages. *Provided per kg of feed: 10 mg copper sulphate, 75 mg Ferrous sulphate monohydrate, 60 mg manganese oxide, 24 mg zinc oxide, 3000 IU vitamin A acetate, 1200 IU vitamin D₃, 30 mg vitamin E, 0.6 mg vitamin K₃, 0.6 mg vitamin B₁, 4.5 mg vitamin B₂, 18.5 mg vitamin B₃, 9 mg vitamin B₅. *ATTD* apparent total tract digestibility, *STTD* standardized total tract digestibility, *SID* standardized ileal digestibility, *ME* metabolic energy; *DE* digestible energy; *NE* net energy.

Hematological indicators

At 112 and 202 days old, two blood samples (5 mL each) of all pigs were drawn from jugular venipuncture using flashback blood collection needles and placed in 9 mL vacutainer blood collection tubes (containing EDTA-2 K or not). Anticoagulated blood was used to determine the hematological indicators. A three-part white blood cell differential count (WBC Diff) were performed using an automated haematology analyzer (DF-900VET, Defeng Biotechnology Co., Ltd., Beijing, China). The clotted blood samples were centrifuged at 2500 rpm for 10 min. Creatinine (CREA), blood urea nitrogen (BUN), BUN/CREA, alanine aminotransferase (ALT), aspartate aminotransferase (AST) and alkaline phosphatase (ALKP) levels in the samples were measured using an automatic Catalyst One Chemistry Analyzer (IDEXX Laboratories, Inc., Westbrook, Maine, USA). The immunoglobulin (Immunoglobulin M (IgM), Ruixin Biotechnology Co., Ltd., Quanzhou, China), cytokines (Interferon-gamma (IFN-γ) and tumor necrosis factor-alpha (TNF-α), Raybiotech Co., Ltd., Guangzhou, China), antioxidant level (Total antioxidant capacity (T-AOC), Nanjing Jiancheng Bioengineering Institute, Nanjing, China), intracellular enzyme (Diamine oxidase (DAO), Nanjing Jiancheng Bioengineering Institute), stress hormone (Cortisol, Nanjing Jiancheng Bioengineering Institute) and insulin-related factors (IGF-1, insulin-like growth factor binding protein-3 (IGFBP-3) and growth hormone receptor (GHR), Nanjing Vazyme Biotechnology Co., Ltd, Nanjing, China) were measured according to the manufacturer's instructions. The primers (5'-3') of insulin-related factors were designed by Sliferz et al.²⁰ including IGF-1-F: TCTTCTACTTGGCCCTGTGCTT and IGF-1-R: CCAGCTCAGCCCCACAGA; IGFBP-3-F: GGCATCCACATCCCCAACT and IGFBP-3-R: CCCC GCTTCCTGCCTTT; GHR-F: CTCCACAGGGCCTCGTACTC and GHR-R: GCTCACATAGCCACACGATG A. The Ct values of the above biomarkers were normalized to the Ct values of the endogenous reference genes, glyceraldehyde 3-phosphate dehydrogenase (GAPDH)-F: ACACACCGAGCATCTCTGACT and GAPDH-R: CGAGGCAGGTCTCCCTAAGC.

Economic performance evaluation

The BWs of three groups of pigs from 104 to 201 days old, along with live pig market prices, feed prices, fixed costs, and piglet prices were used to calculate the revenues. The specific indicator settings and calculation formula are presented in Table 2.

Statistical analyses

WPS Office Excel software (Kingsoft Office Software Co., Ltd., Beijing, China) was used to preprocess the data, and Graphpad Prism 8.4 (Graphpad Software, Inc. San Diego, CA, USA) was used for statistical analyses. The data conformed to a normal distribution or log-normal distribution and exhibited homoscedasticity. Tukey's multiple comparison tests of ordinary one-way Analysis of Variance (ANOVA) were used to study the scores, growth performance, and hematological indicators among the H, M and L groups. Spearman's rank correlation analysis between 13 variables was performed to construct the correlation coefficient matrix. The ggcor package, available in the R programming language version 4.3.0 (<https://mirrors.bfsu.edu.cn/CRAN/>), was employed to visualize the correlation results. The abnormal rate of hematological and biochemical indicators in commercial pigs at 112 and 202 days old across different BW categories was determined. This rate was calculated using the following formula:
Abnormal rate (%) = (Number of abnormal indicators / Total number of indicators) × 100%.
The results were expressed as mean ± standard deviation (SD); *P* < 0.05 was considered statistically significant and *P* < 0.10 was considered as a trend.

Indicators		Setting of reference prices			Symbol
		Low	Medium	High	
Live pig market prices (\$/kg)		2	3	4	A
Piglet prices (\$)		30	40	50	B
Fixed costs (\$/kg/pig)		0.2			C
Feed prices (\$/kg)	For weaned pigs, nursery pigs, and early-stage growing pigs (21–103 d)	0.75	0.65	0.54	D1
	For growing-finishing pigs (104–201 d)	0.5	0.43	0.36	D2
Feed intake (kg)	For weaned pigs, nursery pigs, and early-stage growing pigs (21–103 d) ¹⁷	81.56	56.30	37.64	E1
	For growing-finishing pigs (104–201 d)	Cumulative average feed intake to date			E2
Body weights (kg)		The average body weights of each group on the day of sale			F
Calculation formula					
Revenue = A×F-B-C×F-D1×E1-D2×E2					

Table 2. Indicators and the formula for economic performance evaluation.

Pathogens	High body weight (n = 27)	Medium body weight (n = 25)	Low body weight (n = 27)
PCV2	22.2% (22.79–33.75)*	36.0% (26.78–33.74)	22.2% (20.65–38.88)
PCV3	37.0% (23.80–30.74)	20.0% (26.39–30.84)	37.0% (23.79–32.58)
PRRSV	11.1% (25.72–38.60)	12.0% (27.03–34.91)	22.2% (30.10–34.66)
PRV-gE	70.4% (33.43–34.70)	56.0% (33.06–34.92)	74.1% (33.13–34.94)
CSFV	0.0%	0.0%	0.0%
PEDV	0.0%	0.0%	0.0%
RV	92.6% (31.02–38.60)	92.0% (31.55–38.98)	100% (31.85–38.50)
LI	96.3% (31.25–38.08)	92.0% (31.84–39.15)	92.6 (31.41–39.12)

Table 3. Prevalence of selected pathogens in commercial pigs with different body weights. *The values in parentheses represent the range of CT values. *PCV2* porcine circovirus 2, *PCV3* porcine circovirus 3, *PRRSV* porcine reproductive and respiratory syndrome virus, *PRV-gE* pseudorabies virus glycoprotein E, *CSFV* classical swine fever virus, *PEDV* porcine epidemic diarrhea virus, *RV* rotavirus, *LI* lawsonia intracellularis.

Results
Pathogens detection

The findings from Table 3 revealed a notable presence of mixed pathogen infections among the pigs, with PCV3, PRV-gE, RV and LI exhibiting particularly high prevalence rates across the entire weight categories. The rates for PRRSV and PCV2 demonstrated considerable variation. Notably, CSFV and PEDV were absent from the samples.

Scores

At 112 days old, CS and BCS were significantly different among the H, M and L groups (Table 4). At 152 days old, the H group had a significantly higher CS compared with the other groups ($P < 0.05$). The differences in BCS among the groups persisted for 180 and 202 days old, while no differences were observed in CS.

Growth performance indicators

The three BW groups differed significantly at 70, 112, 152, 180 and 202 days old, as well as the ADFI at 112–152 and 153–180 stages, as presented in Table 3. The significant differences in ADG just existed during the first stage, while in ADFI and FCR were continued to the second stage.

The correlation matrix of 13 growth-related indicators in 79 commercial pigs was shown in Fig. 1. Strong positive correlations were observed among various BW measurements across different time points. Notably, BW at 70 days old showed the strongest correlation with BW at 112 days old ($r = 0.95$, $P < 0.001$). BW was highly correlated with BCS, particularly at 180 days old ($r = 0.93$, $P < 0.001$). The factor most strongly correlated with final BW (202 days old) was BW at 180 days old ($r = 0.90$, $P < 0.001$). Additionally, ADFI from day 112 to 202 showed strong positive correlations with BW at various time points (r ranging from 0.71 to 0.86, $P < 0.001$). Interestingly, FCR from day 112 to 202 exhibited moderate positive correlations with later BWs ($r = 0.57$ to 0.72, $P < 0.001$), but weaker correlations with earlier BWs. CS at both 180 and 202 days showed weak to moderate correlations with most growth indicators.

Indicators	Age (d)	High body weight (n = 27)	Medium body weight (n = 25)	Low body weight (n = 27)
CS	112	4.72 ± 0.25 ^a	4.07 ± 0.31 ^b	3.43 ± 0.35 ^c
	152	4.43 ± 0.30 ^a	4.14 ± 0.23 ^b	4.15 ± 0.23 ^b
	180	4.37 ± 0.36	4.22 ± 0.29	4.20 ± 0.32
	201	4.52 ± 0.32	4.54 ± 0.35	4.43 ± 0.36
BCS	112	4.96 ± 1.56 ^a	1.88 ± 1.09 ^b	− 0.85 ± 1.73 ^c
	180	15.67 ± 2.27 ^a	12.04 ± 2.48 ^b	9.24 ± 1.95 ^c
	201	17.85 ± 1.49 ^a	16.00 ± 1.97 ^b	14.37 ± 1.86 ^c
BW (kg/pig)	24	6.06 ± 0.63	5.81 ± 0.55	5.73 ± 0.56
	70	32.79 ± 3.46 ^a	25.28 ± 2.50 ^b	20.91 ± 2.44 ^c
	112	56.02 ± 4.97 ^a	43.94 ± 4.89 ^b	33.87 ± 4.75 ^c
	152	96.77 ± 8.90 ^a	82.09 ± 6.76 ^b	67.61 ± 8.51 ^c
	180	122.33 ± 10.98 ^a	108.52 ± 9.04 ^b	94.08 ± 9.83 ^c
	201	138.78 ± 13.34 ^a	126.34 ± 12.84 ^b	114.10 ± 12.30 ^c
ADG (kg/pig/d)	112–152	0.99 ± 0.14 ^a	0.93 ± 0.08 ^a	0.82 ± 0.14 ^b
	153–180	0.88 ± 0.17	0.90 ± 0.18	0.90 ± 0.17
	181–201	0.73 ± 0.34	0.82 ± 0.30	0.89 ± 0.21
ADFI (kg/pig/d)	112–152	2.45 ± 0.42 ^a	2.14 ± 0.23 ^b	1.73 ± 0.29 ^c
	153–180	2.84 ± 0.46 ^a	2.66 ± 0.32 ^{ab}	2.39 ± 0.38 ^c
	181–201	2.67 ± 0.68	2.56 ± 0.59	2.58 ± 0.48
FCR (kg/kg)	112–152	2.48 ± 0.29 ^a	2.31 ± 0.20 ^a	2.12 ± 0.26 ^b
	153–180	3.29 ± 0.45 ^a	3.02 ± 0.43 ^{ab}	2.72 ± 0.56 ^b
	181–201	3.46 ± 0.64	3.55 ± 1.51	2.96 ± 0.51

Table 4. Growth performance and health status comparison among commercial pigs of varying body weight categories at different ages. Comparing the same indicator between different body weight groups, the same letter or no letter means no significant difference ($P \geq 0.05$); different letters mean significant difference ($P < 0.05$). *The negative number (an estimated value) indicates that the range is exceeded. CS clinical score, BCS body condition score, BW body weight, ADG average daily gain, ADFI average daily feed intake, FCR feed conversion rate.

Hematological indicators

At 112 and 202 days old, the WBC in the L group was significantly higher than that in the H group ($P < 0.05$), as well as monocyte count (MON#) at 202 days old (Table 5). Other indicators (lymphocyte count (LYM#), lymphocyte percentage (LYM%), and granulocyte percentage (GRA%)) exceeded the reference range and there was no significant difference among the groups. The concentration of BUN in the L group was significantly lower than that in the H and M group at 202 days old.

Using the reference range as the evaluation criterion, we calculated the abnormal rate of indicators (Table 6). The abnormal rates of WBC, LYM#, MON#, LYM%, GRA%, BUN/CREA, and ALT are higher than 50%, and even reach 100%. Compared with 112 days old, the abnormal rate of WBC Diff at 202 days old mostly increased to varying degrees, and the abnormal rate of liver function indicators in biochemical indicators increased, but the abnormal rate of kidney function indicators decreased.

At 202 days old, the $2^{-\Delta\Delta Ct}$ of IGFBP-3 in the L group was significantly higher, other hematological indicators showed no differences in the levels of immunoglobulins (IgM), cytokines (IFN- γ and TNF- α), antioxidants (T-AOC), intracellular enzyme (DAO) and stress hormone (Cortisol) among the groups (Table 7).

Figure 2 presented a comprehensive analysis of the economic performance of pigs with varying BWs under different market conditions. In general, the high BW group (A, D, G) demonstrated superior economic performance, particularly when live pig market prices were elevated. As the market price for live pigs increased from \$1.5/kg to \$2.5/kg (progressing from the top to bottom rows), a notable enhancement in overall economic returns was observed across all BW groups. The data consistently demonstrated that lower feed prices (represented by green lines) yield higher economic returns across all scenarios, thereby underscoring the critical role of feed costs in profitability. In comparison to feed and market prices, the impact of piglet prices (depicted by hollow-dot lines) appeared less pronounced, though it still influenced overall profitability. The curves illustrated disparate growth patterns across BW groups, with the high BW group typically exhibiting higher returns throughout the growth period. The most favorable economic conditions were observed in the bottom row (G, H, I), where market prices were at their peak (\$2.5/kg), especially when combined with lower feed costs. In scenarios with low market prices (A, B, C), specific combinations of elevated feed and piglet prices resulted in negative returns or break-even situations.

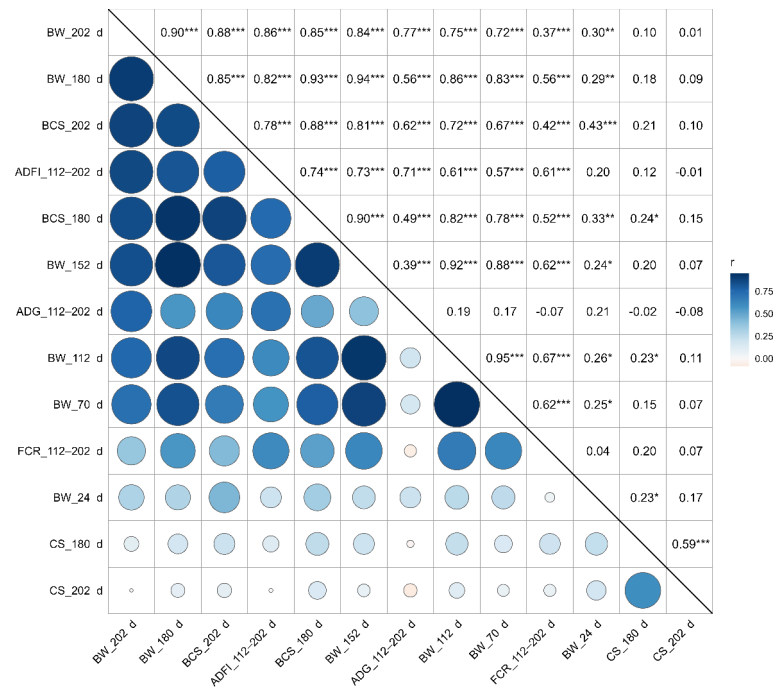


Fig. 1. Correlation matrix of 13 growth-related indicators in commercial pigs. Heatmap displaying Spearman correlation coefficients among 13 growth-related parameters in commercial pigs ($n=79$). Color intensity and size of circles are proportional to the correlation coefficients. The color scale ranges from deep blue (strong positive correlation) through light blue (weak correlation) to light beige (negative correlation). Significance levels: *indicated $P<0.05$, **indicated $P<0.01$, ***indicated $P<0.001$. BW body weight, BCS body condition score, ADFI average daily feed intake, GW gained weight, FCR feed conversion rate, CS clinical core.

Types	Indicators	Reference range*	112 days old			202 days old		
			High body weight (n=27)	Medium body weight (n=25)	Low body weight (n=27)	High body weight (n=27)	Medium body weight (n=25)	Low body weight (n=27)
White blood cell differential count	WBC ($10^9/L$)	4.3–11.5	13.05 ± 6.11^a	14.40 ± 5.96^{ab}	17.76 ± 8.97^b	14.35 ± 5.89^a	16.47 ± 4.69^{ab}	18.21 ± 4.88^b
	LYM# ($10^9/L$)	1.50–4.70	9.05 ± 4.48	9.73 ± 4.13	12.29 ± 6.27	8.09 ± 4.28^a	9.41 ± 3.79^{ab}	11.21 ± 3.83^b
	MON# ($10^9/L$)	0.10–1.00	1.22 ± 0.62	1.36 ± 0.71	1.71 ± 1.03	1.34 ± 0.61^a	1.63 ± 0.58^{ab}	1.85 ± 0.75^b
	GRA# ($10^9/L$)	1.80–7.20	2.77 ± 1.27	3.31 ± 1.40	3.76 ± 1.84	4.93 ± 4.68	5.43 ± 3.93	5.15 ± 3.20
	LYM (%)	26.0–54.0	68.87 ± 5.83	66.96 ± 8.35	68.54 ± 5.57	59.76 ± 20.44	56.87 ± 18.20	62.24 ± 14.29
	MON (%)	1.0–13.0	9.54 ± 2.23	9.20 ± 1.81	9.49 ± 1.88	9.36 ± 1.89	10.17 ± 2.71	9.96 ± 2.59
	GRA (%)	42.0–70.0	21.59 ± 5.61	23.84 ± 8.39	21.97 ± 5.63	31.65 ± 19.99	32.96 ± 18.56	27.80 ± 14.76
Biochemistry	CREA (mg/dL)	0.5–2.1	1.70 ± 0.28 ^a	1.51 ± 0.21 ^b	1.54 ± 0.27 ^{ab}	1.78 ± 0.23	1.78 ± 0.22	1.78 ± 0.18
	BUN (mg/dL)	6–30	5.07 ± 2.25	4.96 ± 3.18	3.70 ± 1.44	10.23 ± 3.23 ^a	8.96 ± 3.66 ^{ab}	7.85 ± 2.44 ^b
	BUN/CREA	6–30	3.04 ± 1.22	2.88 ± 1.03	2.37 ± 1.04	5.81 ± 1.81^a	5.00 ± 1.96^{ab}	4.44 ± 1.42^b
	ALT (U/L)	9–43	67.04 ± 13.99	66.41 ± 12.67	64.11 ± 15.18	66.50 ± 16.77	63.88 ± 12.57	65.41 ± 19.03
	AST (U/L)	16–65	58.48 ± 17.62	62.11 ± 23.39	60.70 ± 32.36	75.60 ± 37.41	79.76 ± 65.40	81.96 ± 58.04
	ALKP (U/L)	92–294	172.67 ± 41.40	188.93 ± 47.26	183.63 ± 41.13	146.73 ± 131.31	127.68 ± 34.10	128.67 ± 33.16

Table 5. Comparison of the hematological indicators among commercial pigs of different body weights. *Reference ranges for white blood cell differential counts and biochemistry indicators were obtained from the manufacturer’s instruction for analyzers used. Values within the same row bearing identical superscript letters or no superscript are not significantly different ($P\geq0.05$), while those with different superscript letters indicate statistically significant differences ($P<0.05$). Values in bold denote measurements that fall above or below the reference range. WBC white blood cell, LYM lymphocyte, MON monocyte, GRA granulocyte, CREA creatinine, BUN blood urea nitrogen, ALT alanine aminotransferase, AST aspartate aminotransferase, ALKP alkaline phosphatase.

Indicators		112 days old			202 days old		
		High body weight (n = 27)	Medium body weight (n = 25)	Low body weight (n = 27)	High body weight (n = 27)	Medium body weight (n = 25)	Low body weight (n = 27)
White blood cell differential count	WBC	48.1%	64.0%	70.4%	76.9%	88.0%	88.9%
	LYM#	77.8%	88.0%	88.9%	80.8%	96.0%	100.0%
	MON#	55.6%	64.0%	77.8%	69.2%	88.0%	81.5%
	GRA#	22.2%	20.0%	18.5%	34.6%	24.0%	14.8%
	LYM%	96.3%	96.0%	96.3%	88.5%	84.0%	88.9%
	MON%	14.8%	0.0%	11.1%	0.0%	16.0%	7.4%
	GRA%	96.3%	96.0%	96.3%	88.5%	92.0%	96.3%
Biochemistry	CREA	7.4%	0.0%	3.7%	3.8%	4.0%	0.0%
	BUN	55.6%	72.0%	92.6%	0.0%	16.0%	11.1%
	BUN/CREA	96.3%	100.0%	96.3%	42.3%	56.0%	85.2%
	ALT	96.3%	100.0%	92.6%	96.2%	96.0%	92.6%
	AST	25.9%	32.0%	22.2%	48.0%	44.0%	44.4%
	ALKP	3.7%	4.0%	0.0%	19.2%	12.0%	11.1%

Table 6. Abnormal rate of hematological and biochemical indicators in commercial pigs at 112 and 202 days old with different body weights. Abnormal rate (%) = (number of abnormal indicators / total number of indicators) × 100%. Bold represents an anomaly rate of ≥ 50%. WBC white blood cell, LYM lymphocyte, MON monocyte, GRA granulocyte, CREA creatinine, BUN blood urea nitrogen, ALT alanine aminotransferase, AST aspartate aminotransferase, ALKP alkaline phosphatase.

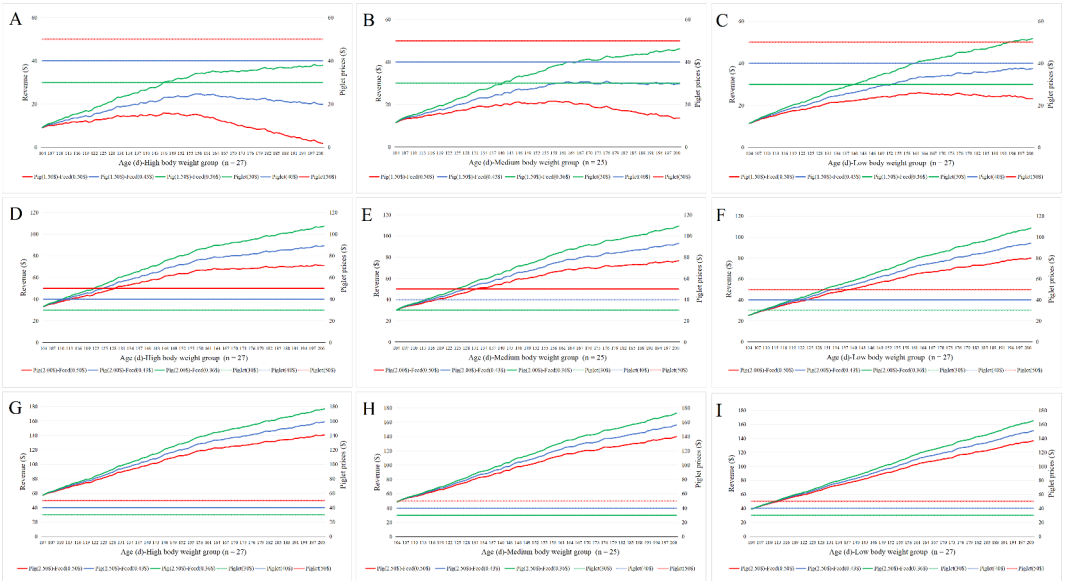


Fig. 2. Economic performance of high, medium, and low body weight groups of commercial pigs under varying market conditions. The 3 × 3 matrix of figures represents different combinations of body weight groups and market prices. Columns from left to right depict high (A, D, G), medium (B, E, H), and low (C, F, I) body weight groups. Rows from top to bottom represent market prices for live commercial pigs at \$1.5/kg (A - C), \$2.0/kg (D - F), and \$2.5/kg (G - I). In all sub-figures, hollow-dotted lines in red, blue, and green indicate piglet prices of \$50, \$40, and \$30/head, respectively. Solid lines represent feed prices: red for \$0.5/kg, blue for \$0.43/kg, and green for \$0.36/kg.

Discussion

This study aimed to evaluate the growth performance and health status of commercial pigs in different BW groups and develop methods to identify slow-growing pigs. The research findings revealed several key insights that provide important management and economic perspectives for commercial pig farming.

Firstly, the study explored methods for assessing BW and health status of commercial pigs. CS, as a comprehensive method of observing individual pigs, provided an initial assessment of overall health status by evaluating body shape, mental state, and activity level. However, the subjectivity of CS may lead to variations

among different assessors. Notably, after 180 days old, there were no significant differences in CS scores among different BW groups (Table 4), highlighting the need to develop more objective and precise indicators for assessing the body condition of commercial pigs.

In contrast, BCS showed a high correlation with BW (Fig. 1), offering a convenient method for assessing commercial pig BW. Unlike sow BCS, which primarily focused on adjusting feed intake from a nutritional perspective, the BCS system for commercial pigs adopted a more comprehensive approach, integrating various aspects including clinical presentation, growth performance, and nutritional status. This method not only enhanced the precision of feed allocation but also aided in the early detection of health issues and optimization of overall herd performance. However, the body condition caliper used in this study was originally designed for sows with a limited measurement range²¹, causing some early-stage fattening pigs' BCS to be out of range (up to 19.5%, data not shown). Therefore, developing a BCS caliper specifically for commercial pigs becomes an important direction for future research.

Secondly, the study defined slow-growing pigs as those weighing less than 110 kg at approximately 200 days old²². Although many variables affected growth performance, slow growth was generally considered to be the result of the interaction of environment, health status, nutrition, and genetic potential in modern production systems^{23–25}. He et al.³ concluded that slow-growing pigs had a lower BW at birth, during weaning, and towards the end of the nursery stage; they also had lower BW at 150 days old. Interestingly, slow-growing pigs showed a certain degree of compensatory growth ability²⁶. This phenomenon was particularly evident in the late fattening stage (180 days old to slaughter), where their ADFI converged with that of other BW groups (Table 4). This compensatory growth pattern suggests a potential for targeted management strategies to optimize the overall growth performance of these initially slow-growing individuals.

To accurately identify slow-growing pigs in the late grower-finisher stage, this study attempted to determine a series of growth-related biomarkers. Hematological analysis indicated the animal's physiological status²⁷. The results showed that the immune cells, including WBC count, LYM#, MON# and LYM (%) exceeded the reference range in all groups (Tables 5 and 6). This indicated that the study pigs were undergoing a continuous immune response to defend against the virus and bacteria²⁸. Lindholm-Perry et al.¹⁶ found that there was a positive correlation between LYM# and ADFI. This can be explained that the creation and maintenance of immune cells needed substantial amounts of energy, resulting in an increase in ADFI²⁹. Serum biochemical indicators reflected metabolic functions of the body³⁰. In terms of biochemical indicators, the BUN of all pigs at 112 days old was lower than the reference range and returned to normal at 202 days old, while the BUN of the L group was still significantly lower than that of the other groups (Tables 5 and 6). This may be related to the insufficient protein intake and low metabolic activity, indicating their lower growth³¹. The ALT existed in liver cytosol and AST existed in heart muscle and liver mitochondria reflecting the functions of the liver and heart³². Under the normal physiological conditions, these contents in the serum were very low. However, ALT of all groups at two-time points was higher than the reference range, indicating that the liver cell membrane, especially for mitochondrial membrane may be damaged by uncertain reasons, thereby disrupting cell integrity and causing them to be released in large quantities into the blood³³. IGF-1, as a growth-promoting factor, is an active protein polypeptide substance necessary for the physiological action of growth hormone³⁴. GHR can induce the expression of IGF-1 by combining it with growth hormones. As the main carrier of IGF-1, IGFBP-3 can mediate the synthesis of growth hormone, but overexpression leads to growth disorders³⁵. Some studies have reported that the growth and development of animals was not completely related to growth hormone, but was positively related to GHR²⁰. This study demonstrated that the expression of IGFBP-3 in the L group was significantly higher (Table 7) and the content of GHR and IGF-1 was positively correlated with BW, which were consistent with previous researches^{36,37}. These findings provided potential indicators for screening and evaluating slow-growing pigs.

The study also revealed the potential impact of sub-clinical infections on pig growth. Results showed the presence of mixed pathogen infections in the study pigs, with particularly high infection rates of PRV-gE, RV

Types	Indicators	High body weight (n = 27)	Medium body weight (n = 25)	Low body weight (n = 27)
Immunoglobulin	IgM (mg/mL)	2.99 ± 3.60	1.23 ± 1.04	1.53 ± 1.29
Cytokines	IFN-γ (ng/mL)	0.52 ± 0.47	0.52 ± 0.97	0.56 ± 0.50
	TNF-α (ng/mL)	0.35 ± 0.25	0.24 ± 0.21	0.44 ± 0.36
Antioxidant Level	T-AOC (mmol/L)	0.34 ± 0.05	0.34 ± 0.04	0.32 ± 0.04
Intracellular Enzyme	DAO (U/L)	9.13 ± 2.03	9.02 ± 1.89	10.14 ± 1.90
Stress Hormone	Cortisol (ng/mL)	100.78 ± 20.94	106.04 ± 25.41	98.99 ± 18.65
Insulin-related factors	IGFBP-3 (2^ΔΔCt)	216.05 ± 328.89 ^a	123.80 ± 129.21 ^a	460.86 ± 406.22 ^b
	GHR (2^ΔΔCt)	1.19 ± 0.75	2.61 ± 0.89	0.96 ± 0.54
	IGF-1 (2^ΔΔCt)	6.80 ± 4.66	6.36 ± 5.13	6.11 ± 4.80

Table 7. Comparison of immunological and physiological indicators among commercial pigs of different body weights at 202 days old. Values within the same row bearing identical superscript letters or no superscript are not significantly different ($P \geq 0.05$), while those with different superscript letters indicate statistically significant difference ($P < 0.05$). IgM immunoglobulin M, IFN-γ interferon-gamma, TNF-α tumor necrosis factor-alpha, T-AOC total antioxidant capacity, DAO diamine oxidase, IGF-1 insulin-like growth factor 1, GHR growth hormone receptor, IGFBP-3 insulin-like growth factor binding protein-3.

and LI (Table 3). The prevalence rates of PRRSV and PCV2 vary significantly and may be influenced by a variety of factors, such as age, BW, immune status, and environmental conditions. CSFV and PEDV were not detected in these samples, which may suggest that effective vaccination or disease control measures are in place. This may be one reason for the low correlation between clinical scores and BW (Fig. 1). During the infection, the changed of appetite and metabolism resulted in weight loss or growth rate decline³⁸. Serum cytokines can be used as biomarkers of persistent infection, but they appeared only in the acute phase of infection¹². Therefore, in this study, even though the WBC in the L group was significantly higher than that in other groups, no significant differences were observed in IFN- γ and TNF- α levels (Table 7). Nevertheless, TNF- α appeared inversely proportional to BW. However, due to the limited frequency of blood sampling, some hematological indicators did not correlate with growth as expected. Future research needs to conduct more frequent blood sampling to better understand the relationship between these indicators and growth.

Finally, a comprehensive evaluation of the economic performance across different pig BW groups (high, medium, and low) was conducted, with a particular focus on slow-growing pigs (Fig. 2). The analysis incorporated various market conditions, considering swine market prices, feed costs, fixed expenses, and piglet prices from China and the United States, two major pork-producing countries^{39,40}. The economic returns across all BW groups were highly sensitive to fluctuations in live pig market prices, feed costs, and piglet prices. Notably, feed costs emerged as a critical determinant of economic efficiency, with lower feed prices consistently yielding higher economic returns across all scenarios. In low market price scenarios, the break-even point for the low BW group was found to be comparable to, or even more favorable than, other BW groups. However, under medium and high market price conditions, the low BW group consistently reached the break-even point later than the other groups. These findings have significant implications for pig producers and farm managers, emphasizing the need for adaptive management strategies that consider the dynamic interplay between BW, market conditions, and production costs. During periods of depressed market prices, producers may need to tailor management approaches for low BW pigs to capitalize on their potentially earlier break-even points. Conversely, when market prices were medium to high, focusing resources on higher BW groups may yield superior economic returns. This comprehensive economic analysis provided valuable decision-making references for pig producers, enabling more accurate assessment of the impact of growth rates on economic efficiency in pig farming. It underscored the importance of adapting management strategies to market dynamics and pig characteristics to optimize economic outcomes.

Future research will focus on several interconnected areas: developing a BCS caliper specifically designed for commercial pigs; conducting longitudinal studies tracking long-term trends in BCS and BW; evaluating the effects of various management interventions on slow-growing pigs; investigating the synergistic impacts of genetic and environmental factors on growth rates; and analyzing the long-term economic implications of different BW management strategies. These multifaceted research efforts aim to contribute significantly to the development of more effective and economically viable pig management strategies in commercial settings, ultimately enhancing the productivity and sustainability of the pig farming industry.

Conclusions

This study successfully evaluated the growth performance and health status of commercial pigs in different BW groups. The research found that BCS was highly correlated with BW, providing a convenient method for BW assessment. It established a threshold of 114 kg slaughter BW for defining slow-growing pigs and identified WBC count, IGFBP-3, and BUN as potential biomarkers. Economic analysis revealed the sensitivity of all BW groups to market condition changes, particularly the significant impact of feed costs. Low BW groups performed better under low market prices but reached break-even points later in medium to high-price environments. These findings provided more effective BW assessment and management tools for commercial pig farming, laying the foundation for improving production efficiency and economic benefits.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to company confidentiality policies but are available from the corresponding author on reasonable request.

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Author contributions

Ran Guan were responsible for the study design. Ran Guan and Zhiqiang Hu drafted the manuscript. Yang Li and Yuntong Shi was responsible for the testing of samples. Zhiyuan Chen offered the data of grow performance. Lulu Li and Zheng Yan collected the samples. Lili Wu and Xiaowen Li reviewed the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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