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Abstract This study was to investigate the effects of housing systems (loose housing vs. tie stalls) in the finishing beef bulls. A total of 119 bulls were collected from the same farm, with an average live weight of 681 kg. The sample comprised 58 loose-housing bulls and 61 tie-stall bulls, each treatment group has six replicates, with a fattening period of approximately 5 to 9 months. These animals were utilized for comparative research on the impact of housing systems on physical activity, blood parameters, live animal traits, carcass characteristics, and meat quality. These traits are affected by the housing systems ($P<0.05$ or $P<0.01$). Compared with tie-stall bulls, loose-housing bulls exhibited longer periods of physical activity (6.76 h/day vs. 3.61 h/day) and different daytime activity patterns, blood parameters closer to health norms, similar dressing percentages (58.80% vs. 58.97%), lighter bone weights (55.86 kg vs. 66.86 kg), heavier liver weights (7.91 kg vs. 6.51 kg), and more developed hind limb muscles. The supraspinatus, longissimus lumborum, and semitendinosus muscles exhibited less redness (CIE a* 15.75–18.71 vs. CIE a* 16.03–23.86) and darker meat color (CIE L* 28.49–30.67 vs. CIE L* 28.31–35.07). Additionally, loose-housing bulls had lower muscle shear force (47.41–49.09 N vs. 60.14–89.71 N). Notably, the semitendinosus muscle showed the highest level of responsiveness to housing systems in terms of meat quality traits. In conclusion, loose housing is more advantageous for animal welfare, growth rate, meat yield, and tenderness for finishing beef bulls compared with tie stalls.

Keywords: Beef housing systems, Physical activity, Carcass characteristics, Meat quality, Xinjiang brown cattle

Introduction

Following socio-economic progress, post-2013 saw a proliferation of intensive finishing beef enterprises with capacities of 10,000 head or more in Xinjiang province, China. These enterprises primarily raise breeds with superior meat production performance, including Xinjiang brown cattle (XBC) (Wang et al., 2023), Angus, and Simmental cattle. Modern practices include the use of maize silage-based roughage and maize-mixed meal concentrates in total mixed rations (TMR), ad libitum feeding, high proportions of loose housing, feed processing, transport feeding, and large-scale mechanical clearance of fecal contamination. This trend gradually replaces traditional practices (Savoia et al., 2019), such as smaller herd sizes, mixed breeds, and restricted concentrate feeding, where all animals were tie. This trend mirrors that observed in the EU (Hocquette et al., 2018), where loose housing systems are displacing traditional tie systems.

Two broad categories of beef production systems can be identified: ‘extensive’ and ‘intensive’ (Clinquart et al., 2022). Housing systems are a component of production systems, which are broadly divided into two categories (Gallo et al., 2017): loose and tie, corresponding to ‘extensive’ and ‘intensive’ production systems, respectively (Dunne et al., 2011). Loose housing can be subdivided into four types: feedlot, hoop barn, loose housing/barn, and pasture (Park et al., 2020). The enterprises in this study adopted a modern approach, primarily differing in the choice between loose housing/barn and tie stalls (Fig. 1). In this study, the average price per kg of live cattle in loose housing was 1 to 1.5 RMB higher than in tie stalls. The rationale behind this pricing discrepancy warrants further investigation, as it is important to finishing beef enterprises and animal scientists alike. Literature indicates that housing systems significantly affect beef cattle welfare (Starvaggi Cucuzza et al., 2014; Tuomisto et al., 2015), growth performance (Huuskonen et al., 2008; Keane et al., 2017), carcass characteristics, and meat quality (Gallo et al., 2017; Savoia et al., 2019). Notably, these factors are generally superior in

loose housing compared to tie stalls, with differences in cattle activity attributed to varying space allowances (Ingvartsen and Andersen, 1993).

However, domestic research on housing systems and their impact on beef cattle performance in China is lacking. Understanding of loose housing versus tie stalls remains insufficient and controversial. The transformation and modernization of finishing beef enterprises have led to changes in housing systems, along with increasing consumer concerns regarding meat origin, production methods, rearing conditions for livestock, and animal welfare—critical factors in the overall perception of meat quality (Moloney et al., 2001). There is an urgent need for scientific research and comprehensive analysis of these issues.

This study aims to compare differences in physical activity, blood parameters, live animal traits, carcass characteristics, and meat quality between loose housing and tie stalls for finishing beef bulls. The research seeks to deepen understanding of how housing systems affect these traits and provide a basis for selecting housing systems to improve animal welfare, meat production capacity, and meat quality.

Materials and Methods

Animals and experimental management

From May to December 2023, 119 XBC with an average weight of 681 kg (Fig. 2A,Fig. 2B) were collected from the same commercial finishing beef enterprise for slaughter. This group included 58 bulls (28±5.2 mon) in the loose-housing treatment (L) and 61 bulls (32±4.7 mon) in the tie-stalls treatment (T) (Fig. 2C, Fig. 2D). The trials were based on field data. The L group collected 10 bulls from one pen in May and 48 bulls from 5 batches in December from 5 different pens in December at 9, 9, 10, 10, 10/cattle per pen; this equates to 6 replicates of 9–10 bulls each. T group collected 10 bulls from one house in May and 51 bulls from 5 batches in July from 5 different houses with 11, 10, 10, 10, 10/cattle per house, again giving 6 replicates of

10–11 bulls per replicate. The farm has a total of 45 loose housing pens, 21 tie stalls houses, and 14 other types of barns. Without interfering with the normal production of the cattle farm, we endeavored to randomly select the cattle distributed in the pen/house at different locations of the cattle farm for the experiment, and the exact locations are shown in the Supplementary Materials Fig. 1 and Fig. 2. The bulls were slaughtered in a replicated manner, and the replication was in accordance with the pen distribution. As a result, the aforementioned replication, pen distribution, and slaughter order were integrated and regarded as a batch effect. These animals were purchased by finishing beef enterprises from breeders in the pasture area or live animal markets when their weight reached approximately 250–270 kg (approximately 9–12 mon). They were then transferred to isolation pens for deworming, gastrointestinal health maintenance, and vaccination. After two months, once deemed healthy and free from disease and their weight reached approximately 280–300 kg, they were moved from isolation pens to growth pens (loose-housing) for further development. When the cattle's weight reached 450–470 kg, they were transferred from growth pens to fattening pens for approximately 5–9 mon; some were housed in loose facilities while others resided in tie-stalls. When their weight reached approximately 650 kg, they were slaughtered based on market demand considerations.

The space allowance for the two housing systems was 80–100 bulls per loose-housing pen (10–13 m²/cattle) and 400 bulls per tie-stalls house (2–2.5 m²/cattle). The loose pen features a 1/9 rain-proof and shaded roof in the center of the field, with walls on three sides and an open side for free access. It has a ventilated area between the roof and walls, a concrete bedded area, and soil flooring in the rest of the activity area. Bulls in tie-stalls are tethered in single stalls separated by rails within a house with a concrete bedded area. An 80 cm rope restricts their movement, allowing only standing and lying down. The bulls had continuous access to fresh water and mineral salt blocks. Their diets comprised maize silage-based roughage and maize-mixed meal-based concentrates, provided as TMR (Table 1). All feeds were administered twice

daily at 9:00 AM and 7:00 PM, ensure that an average TMR of 22.5 kg per cattle per day is supplied to both the L group and the T group (Table 1). Additionally, make sure that the feed intake among the cattle within each group is generally consistent.

Animals physical activity/exercise and behaviors monitor

The XN-ACT-B 3.0 smart collar (Litrace Beijing Co., Ltd., Beijing, China) utilizes NB-IoT communication, a bovine movement algorithm model, and cloud data analysis to continuously monitor and collect behavioral and physical activity data from experimental bulls. The collar operates 24 h a day, categorizing activity into three levels: low (e.g., ruminating, resting, or lying still), medium (e.g., feeding, standing, or walking), and high (e.g., fighting, chasing, or running). Smart collars were used for real-time physical activity monitoring, with data statistically analyzed and uploaded to a cloud-based system at regular intervals (2 h). Thirty cattle—15 from each treatment group (L and T)—were equipped with smart collars during the trial period from July 13 to November 21, 2023. Data from the middle week of each month were selected to represent the monthly averages.

Complete blood cell count and serum chemistry profile analysis

40 L (4 batches of cattle in May and December) and 50 T (5 batches of cattle in May and July) cattle were selected for blood analysis. Two 10 mL tubes of blood were collected from the coccygeal (tail) vein; one tube contained ethylenediaminetetraacetic acid (EDTA), while the other had no additive. All samples were promptly stored in a sealed foam box on ice at 0–4℃ and transported to the laboratory. Complete blood cell count (CBC) was performed on the EDTA-treated whole blood samples using a veterinary hematology automated analyzer (Vetcan HM5, Abaxis, Inc., Union City, CA, USA). The following 24 parameters were measured: red blood cell (RBC) count, hemoglobin (Hgb), hematocrit (HCT), mean corpuscular volume

(MCV), mean corpuscular hemoglobin (MCH), mean corpuscular hemoglobin concentration (MCHC, calculated as MCHC = [Hgb/HCT] × 100), RBC distribution width coefficient of variation (RDW_CV), RBC distribution width standard deviation (RDW_SD), white blood cell (WBC) count, neutrophils (NEU), eosinophils (EOS), basophils (BAS), lymphocytes (LYM), monocytes (MON), NEU% = [NEU/WBCs] × 100%, EOS% = [EOS/WBCs] × 100%, BAS% = [BAS/WBCs] × 100%, LYM% = [LYM/WBCs] × 100%, MON% = [MON/WBCs] × 100%, platelets (PLT), mean platelet volume (MPV), PCT = [platelet count × MPV]/10,000, platelet distribution width coefficient of variation (PDW_CV), and platelet distribution width standard deviation (PDW_SD), reference interval (Underwood et al., 2015).

A complete biochemical analysis of serum samples was conducted using a veterinary chemistry automated analyzer (MiniLab Vet, Chengdu Seamaty Technology Co., Ltd., Chengdu, China), following the manufacturer's instructions and incorporating automatic software updates, cleaning, and quality control procedures. The following 24 parameters were measured: total proteins (TP), albumin (ALB), globulin (GLOB), the ratio of albumin to globulin (A/G), total bilirubin (TB), total bile acids (TBA), gamma-glutamyl transferase (GGT), aspartate transaminase (AST), alanine aminotransferase (ALT), alkaline phosphatase (ALP), lactate dehydrogenase (LDH), amylase (AMY), lipase (LPS), creatine kinase (CK), creatinine (Crea), uric acid (UA), urea (UREA), the ratio of uric acid to creatinine (U/C), glucose (GLU), total cholesterol (TC), triglyceride (TG), total carbon dioxide (tCO_2), calcium (Ca), and phosphorus (PHOS), reference interval (Underwood et al., 2015).

Live animal traits measurements

The bulls were weighed and body trait measurements, including chest girth, wither height (Boer et al., 1974), stature (measured from the anterior edge of the shoulder joint to the posterior edge of the sciatic bone using a tape measure) (Yang et al., 2019), and hip width (Kirkpatrick et

al., 2023). Coccygeal (tail) vein blood collection and ultrasonic measurements were conducted 3–5 h prior to slaughter. Ultrasonic measurements were performed by two technicians, one using a probe (18 cm, 3.5 MHz linear array transducer) pressed against the bull's back while the other used a diagnostic real-time ultrasonic host (MyLabTouch, Esaote, Genoa, Italy) for interpretation, minimizing inter-operator differences. The cattle were immobilized in the weighing pen and scanned in a quiet, relaxed position to obtain accurate sound images.

Ultrasonic procedures closely aligned with those outlined by Avilés et al. (2015). Live animal measurements followed protocols described by Bergen et al. (1997) and Wall et al. (2004), including assessment of the longissimus thoracis (LT) muscle area between the 12th and 13th ribs, referred to as ultrasonic rib eye area (UREA); ultrasonic subcutaneous fat thickness (UFT) over the LT at a point 3/4 the length ventrally; ultrasonic longissimus thoracis thickness (ULT), and ultrasonic intramuscular fat content or marbling (UIMF), measured in the longitudinal image of the LT directly over the 12th and 13th ribs.

Slaughtering and procedures

Upon reaching commercial weight (approximately 650 kg for XBC), the bulls were fed at 7 PM on the day before slaughter, then loaded onto trucks and transported to an officially approved commercial abattoir (Yining, Xinjiang, China), approximately 30 min and 20 km from the feedlot. Upon arrival at the abattoir at 10 PM, they were placed in lairage pens for 12 h without access to food or water. All bulls were subjected to uniform transportation conditions and handling procedures. The animals were weighed between 8–10 AM the following day, followed by slaughter and dressing according to standard commercial protocols. Electrically stimulated stunning was not utilized during processing.

Carcasses characteristics measurements and sampling

Carcass data were collected by trained personnel, with hot carcass weight representing the sum of the two carcass halves measured at the processing plant prior to entering the chiller (Coleman et al., 2016). Dressing percentage was calculated as the ratio of hot carcass weight to preslaughter live body weight (Wang et al., 2021). Net meat weight (NMW) referred to hot carcass weight excluding bone (Bordbar et al., 2020), while net meat percentage was determined as the proportion of NMW to preslaughter live body weight, and bone percentage was calculated as the proportion of bone weight to hot carcass weight (Honig et al., 2020). Within 40 min after slaughter, 100 g samples of each supraspinatus (SU), longissimus lumborum (LL), and semitendinosus (ST)—representing the anterior, middle, and posterior carcasses with varying contractile and metabolic properties were removed from the left half of the hot carcasses (Vestergaard et al., 2000; Picard et al., 2014).

The carcasses were chilled at 4 ℃ for 24 h. Subsequently, measurements were taken on the left half-carcass, including carcass length and hind limb length as outlined by Boer et al. (1974); hind limb perimeter measurements as per Avilés et al. (2015); carcass depth (measured at the level of the seventh rib from the dorsal edge of the seventh thoracic vertebra spinous process to the ventral edge of the seventh sternebra); hind limb width (measured from the medial caudal root depression to the anterior edge of the thighs); hind limb meat thickness (vertical distance from the body surface of the posterior thigh to the midpoint of the femur using an awl); and between ribs meat thickness (distance of penetration of the flesh between the midpoints of the 6th and 7th ribs using an awl) (Yang et al., 2019). Subcutaneous fat thickness (FT) and rib eye area (REA) were measured between the 12th and 13th ribs. The area of the rib eye muscle was covered with translucent sulphate paper, an outline of the area was drawn with a pen, and a 1 cm × 1 cm clear Plexiglas ruler was used to cover the sulphate paper with the outline. Manual counting was performed, and the size of REA was calculated. The entire SU, ST, and 1 kg of LL muscles at the 13th rib to the 2nd lumbar vertebra section were removed from the left half of the

carcass by a professional butcher, vacuum-packed, immediately frozen at -20 ℃, and transferred to the laboratory for further analysis.

Meat Quality Analysis

The vacuum-packed raw meat cuts were thawed in a refrigerator at 4℃ for 24 h to assess meat quality. The ultimate pH at 24 h (pH_{24h}) was measured using a portable pH meter (testo 205, Testo SE & Co. KGaA, Baden-Württemberg, Germany) calibrated with standard buffers (pH 4.0 and 7.0). The electrodes were inserted approximately 1 cm into the muscle tissue.

Color was assessed using a colorimeter (Chroma Meter CR-410, Konica Minolta, Inc., Tokyo, Japan) on the freshly cut surface, perpendicular to the direction of the muscle fibers, after a 1 h bloom period at 4℃. The instrument was calibrated with its white reference tile and set with illuminant D65 (color temperature 6500 K), representing average daylight. CIELAB coordinates including lightness (CIE L*), redness (CIE a*), and yellowness (CIE b*) were recorded.

Water-holding capacity (WHC) was determined by measuring pressure loss percentage (PL) using a modified Grau and Hamm method, as described by Beriain et al. (2000). This involved using a pie-shaped indenter fitted to a texture analyzer (EZ-LX, Shimadzu (Suzhou) Instruments Manufacturing Co., Ltd, Suzhou, China) to compress 5 g meat samples under 350 N for 5 min. Additionally, a circular sampler with a 25.4 mm diameter was employed to drill a meat sample of approximately 5 g.

A 8 cm × 4 cm × 4 cm cuboid of meat, weighing between 100–120 g, was prepared to assess cooking loss (CL) and Warner-Bratzler shear force (WBSF). The beef cuboid was sealed in a polyethylene bag and cooked in a water bath preheated to 75℃ until it reached an internal temperature of 70℃. Cooking temperature was monitored using a portable food thermometer (8899, Deli Group Co., Ltd., Ningbo, China) inserted into the geometric center of the cuboid. After reaching the desired temperature, the cuboid was removed from the water bath and cooled

for 30 minutes under tap water to prevent further cooking. It was then removed from the bag, blotted dry, and reweighed (Honikel, 1998).

CL% was calculated as the weight difference between the raw and cooked beef cuboid, expressed as a percentage of the raw beef cuboid weight. A texture analyzer's supplied circular sampler with a 12.7 mm diameter was used to shear samples perpendicularly to the longitudinal orientation of the muscle fibers using a V-shaped Warner-Bratzler cutting blade (EZ-LX, Shimadzu (Suzhou) Instruments Manufacturing Co., Ltd, Suzhou, China). WBSF was measured as the maximum force (Newtons) required to shear the cylindrical core at a crosshead speed of 50 mm per min.

Hematoxylin-eosin (HE) stained muscle slide preparation and analysis

The meat samples were fixed in 4% paraformaldehyde for over 24 h, followed by trimming, dehydration, embedding, sectioning, and staining with HE. Subsequently, the samples were sealed and subjected to microscopic examination for quality assessment (Mairinoja et al., 2023). The HE-stained microscope slides were scanned using a FLASH digital slide scanner (Pannoramic 250, 3DHISTECH, Budapest, Hungary) at ×20 magnification with a resolution of 0.23 μm/pixel. The scanned file was opened with CaseViewer 2.4 software (3DHISTECH, Budapest, Hungary), and the area of the muscle tissue was selected for 400x imaging, filling the entire field of view with tissue to ensure consistent background lighting. After imaging, Image-Pro Plus 6.0 software (Media Cybernetics, Maryland, USA) was utilized to measure the diameter of five muscle fibers in each photo in millimeters. The total number of muscle fibers in each photo was counted. The mean cross-sectional areas (CSA) of muscle fibers were calculated as total CSA / total number of muscle fibers; muscle fiber density was calculated as total number of muscle fibers/total CSA.

Meat chemical composition analysis

Raw meat samples were homogenized in a knife mill (MQ7030X; De'Longhi Braun Household GmbH, Romania) and analyzed for water, crude protein, and ether extract contents according to Association for Official and Analytical Chemists (AOAC) procedures (Hasan, 2015). Instruments used included a precision blast drying oven (BAO-250A; STIK Co., Ltd, Shanghai, China), an automatic Kjeldahl nitrogen analyzer (K9840; Hanon Advanced Technology Group Co., Ltd, Jinan, China), and a Soxhlet extraction apparatus (SZF-06A; Shanghai Xinjia Electronic Co., Ltd, Shanghai, China).

Statistical analysis

Statistical analyses were performed using R version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria). All data were initially organized in Microsoft Excel 2021 (Microsoft, Seattle, WA, USA), and the "readxl" package was utilized in R to import the data. The "car" package was used to remove observations outside the range of 3 standard deviations from the mean for each trait using the outlierTest() function. All traits were analyzed using the linear mixed procedure from the "lmerTest" package with the lmer() function, except for physical activity/exercise, blood parameters, and body weight, which were analyzed by one-way ANOVA using the aov() function. The "emmeans" package was used for multiple comparisons with the Bonferroni test for fixed-effects least squares means via the emmeans() function. Results are presented as least squares means (LSM) with standard error of the mean (SEM). The "ggplot2" package was used to create descriptive statistics graphs with the ggplot() function.

Live animal and carcass-related traits were analyzed using the following linear mixed model (1):

$$y_{ijkl} = \mu + H_i + W_j + H \times W_{ij} + B_k + e_{ijkl} \quad (1)$$

where y_{ijkl} is the observation of each trait; μ is the overall mean; H_i is the fixed effect of the housing systems (i = L, T); W_j is the fixed effect of body weight (j = 6 classes: 551–600 kg, 601–650 kg, 651–700 kg, 701–750 kg, 751–800 kg, 801–850 kg) (Savoia et al., 2019); $H \times W_{ij}$ is the interaction between housing systems and body weight; Bk is the random effect of the batch on the day of slaughter (12 levels) and e_{ijkl} is the residual error. Batch and e_{ijkl} were assumed to be normally and independently distributed as $\sim N(0, \sigma^2)$.

Meat quality and myofiber-related traits were analyzed using the following linear mixed statistical model (2):

$$y_{ijklmn} = \mu + H_i + M_j + C_l + H \times M_{ij} + H \times C_{il} + M \times C_{jl} + H \times M \times C_{ijl} + B_k + A_m + e_{ijklmn} \quad (2)$$

where H_i, B_k and e_{ijklmn} are defined as in model (1); M_j is the fixed effect of the different muscles (j = SU, LL, ST); C_l is the fixed effect of the carcass weight (l = 4 classes: 301–350 kg, 351–400 kg, 401–450 kg, 450–500 kg); A_m is the random effect of the animal ID (119 levels). A minimum of 3 observations per individual was required for both the batch and animal ID.

Results and Discussion

Animals' physical activity/exercise and behaviors

A five mon monitoring period revealed significant differences ($P<0.01$) in low, medium, and high levels of physical activity between the L and T groups on an average day (Table 2). Fig. 3A. demonstrates that both treatments exhibit a resting period of low-level physical activity from 0:00 to 7:00, with overlapping lines and consistent trends. Between 8:00 and 10:00, both treatments enter their first active period of the day, peaking approximately 9:00, coinciding with morning feeding. This period displays several distinct 'V' shapes. The second active period occurs between 18:00 and 20:00 for T, and 20:00 to 22:00 for L, with peaks at approximately

19:00 for T and 21:00 for L, corresponding to afternoon feeding times. This period also exhibits multiple distinct 'V' shapes. The line graphs depicting physical activity levels between 09:00 and 19:00 for both treatments show distinct differences. In L, low and medium levels of physical activity closely intersect, while in T, these levels remain widely separated. Furthermore, Fig. 3B. shows that both treatments exhibited significantly distinct physical activity levels in July compared to other months.

Considering the medium and high levels of physical activity in the trial as the total time spent grazing and voluntarily engaging in locomotion, it is evident that the 406 min per 24 h (6.76 h) for each L bull and 217 min per 24 h (3.61 h) for each T bull are significantly lower than the 30 to 110 min of locomotion and 500 to 600 min of mobile grazing reported by Fraser and Broom (1996) for cattle in 'free-range' conditions in Australia, South Africa, New Guinea, and the USA. In these regions, cattle typically move for approximately ten h per day. Thus, under artificial conditions with adequate water and food but limited space, the total time spent on voluntary locomotion and mobile grazing is significantly reduced. High levels of physical activity are primarily caused by competition for food, and the herd is amenable outside of feeding time.

In Fig. 3A. both L and T bulls exhibit distinct 24 h circadian rhythms, with significant differences in daytime activity patterns attributed to tethering. Jurie et al. (2006) suggested that "it is tempting to speculate that in cattle, spontaneous, regular, and low-level physical activity, such as that observed on pastures, may be sufficient to regulate muscle metabolic properties." Consequently, L bulls are more aligned with this speculation than T bulls, promoting normal muscle metabolism and facilitating near-natural behaviors like grooming, which is essential for overall cattle welfare (Dickson et al., 2024).

Furthermore, Fig. 3B. shows that both treatments exhibited significantly distinct physical activity levels in July compared to other months, likely due to the stress of wearing smart collars and regrouping. Marumo et al. (2024) noted that cow regrouping significantly disrupted

behavioral dynamics and activity budgets, impacting milk yield, composition, physical activity, and rumination time. A marked increase in solitary activity and a decrease in feeding and rumination were observed on the day of regrouping (0 d) and the following day (+1 d), compared to the day before grouping (-1 d). However, milk fat content and interaction time among cows were still affected six days after regrouping (+6 d). The trial bulls were collared and regrouped on July 13th, with physical activity counts recorded from July 15th to 21st, capturing an uptick in medium-level physical activity alongside a decline in low-level physical activity during the week following the stressor. By August, normal activity patterns had stabilized among the cattle.

Complete blood cell count and serum chemistry profile

Regarding the CBC (Table 3), no differences in RBC-related parameters were found between the T and L groups ($P>0.05$), except for MCHC, which fell below the reference range. In leukocyte-related parameters, total WBC, NEU, and NEU% were higher in the L group than in the T group ($P<0.01$), while BAS, EOS%, BAS%, and LYM% were elevated in the T group ($P<0.05$ or $P<0.01$). Notably, EOS, LYM, MON, and MON% showed no differences between T and L ($P>0.05$), with all values within the reference range except for EOS. The platelet count was higher in the T group compared to L ($P<0.05$ or $P<0.01$).

The low MCHC levels in both treatments may indicate regenerative anemia (Jones and Allison, 2007). The NEU to LYM ratio approached 1:1, deviating from the normal ratio of 1:2 and the stress leukogram of 2–3:1 (Jones and Allison, 2007), suggesting mild stress in both treatments, likely due to driving, loading, and transportation processes. The L group appeared to experience a stronger stress response than the T group. Daly et al. (1999) noted that pasture-reared cattle are more susceptible to muscle glycogen depletion than feedlot-reared cattle due to greater sensitivity to environmental stressors during transport and handling prior to slaughter, which supports our findings. Elevated BAS, EOS%, and BAS% in the T group suggest increased

immune responses to allergic and inflammatory processes (Jones and Allison, 2007). The significant difference in PLT levels between treatments may be attributed to variations in blood sample collection timing and prolonged exposure to EDTA (Jones and Allison, 2007).

In the serum chemistry profile (Table 4), TP, AST, ALT (values above the reference range), ALP, LDH, and CK were lower in the T group than in the L group ($P<0.05$ or $P<0.01$). Conversely, AMY (values above the reference range), LPS, GLU, and Ca were higher in the T group ($P<0.05$ or $P<0.01$). No other parameters differed significantly between T and L ($P>0.05$).

The TP levels in both treatments may indicate mild dehydration. Additionally, GGT levels suggest potential hepatobiliary disease and cholestasis (Braun et al., 1983), though this was less severe in the L group. Elevated AST, LDH, and CK levels in the L group point to possible muscle damage rather than liver disease (Russell and Roussel, 2007), consistent with vigorous fighting and exercise among L bulls. Furthermore, elevated blood glucose, amylase, and lipase levels in the T group indicate potential pancreatic inflammation (Szatmary et al., 2022). Finally, calcium concentration in the T group suggests potential acidosis, leading to increased ionized calcium from ALB and other proteins (Russell and Roussel, 2007).

Live Animal Traits

Mean weights of the two treatments were similar ($P>0.05$), as shown by close overlap in kernel density plots, despite a nearly four mon difference in mean age and a slightly larger standard deviation in body weight for L compared to T (Table 5, Fig. 2B). All body size traits were affected by body weight ($P<0.01$), while none of the housing system effects reached significance ($P>0.05$). An interaction between body weight and housing systems was observed for wither height ($P<0.05$). Ultrasound-measured traits were influenced by body weight ($P<0.05$ or $P<0.01$), except for UIMF ($P>0.05$), while UREA and UIMF were affected by the housing system ($P<0.1$).

The higher growth rate in L compared to T can be attributed to differences in space allowance. The space allowance for L is 10–13 m²/cattle, significantly exceeding critical values of 4.5 m²/cattle and 4.7 m²/cattle reported by Keane et al. (2017) and Ingvartsen and Andersen (1993), respectively. Beyond this threshold, average daily live weight gain (ADG) can reach 100%. In contrast, T has a space allowance of only 2–2.5 m²/cattle, below this critical value, resulting in an ADG lower than 100%. Additionally, limited space for T may lead to stress, reducing feed intake and increasing muscle and fat breakdown. The higher UREA level and lower UIMF content in L compared to T are consistent with previous research summarized by Ingvartsen and Andersen (1993), indicating that loose housing results in greater REA and less fat deposition than tethered housing due to increased exercise leading to more muscle mass.

Carcass characteristics

Slaughter traits were influenced by body weight ($P<0.1$, $P<0.05$, $P<0.01$), except for dressing percentage, net meat percentage, and FT ($P>0.05$) (Table 6). Net meat percentage, bone weight, bone percentage, and meat-to-bone ratio were also affected by housing systems ($P<0.1$, $P<0.05$, $P<0.01$). Additionally, all organ weights were influenced by body weight ($P<0.05$ or $P<0.01$), while hide, liver, kidney and perirenal fat weights were similarly affected by housing systems ($P<0.05$ or $P<0.01$). Significant interactions between body weight and housing systems were observed for head, hide, back hooves, and liver ($P<0.1$, $P<0.05$, $P<0.01$). Cold carcass body size traits were affected by body weight ($P<0.05$, $P<0.01$), and carcass length, depth, hind limb width, hind limb meat thickness, and between-ribs meat thickness were affected by housing systems ($P<0.1$, $P<0.05$, $P<0.01$).

The dressing percentage for both treatments fell within the range of 600–780 kg for Fleckvieh (58.5–59.7%) (Honig et al., 2020). Carcass characteristics, influenced by sex, age, and genetic factors, especially breed, primarily impact dressing percentage (Clinquart et al., 2022). The rates

of muscle and fat growth, along with their ratios, vary significantly among cattle breeds during growth and fattening (Jaborek et al., 2023), with this variation depending on breed maturity (Honig et al., 2020). Farming practices, particularly feeding and energy intake, also influence carcass characteristics by affecting growth rate and maturity. When other factors remain constant, the secondary factor of housing system did not cause notable discrepancies in slaughter rates between treatment bulls (Soulat et al., 2016).

The L bull had a bone weight 11 kg lighter than that for the T bull, attributed to its faster growth rate and being approximately four mon younger at the same slaughter weight. Comparing Fleckvieh bulls at 600 kg body weight (67.8 kg bone weight) at 12 mon with those at 780 kg (79.9 kg bone weight) at 17 mon shows that bones continue to grow slowly until reaching mature weight (Honig et al., 2020, 2022). The bone percentage of L fell within the Fleckvieh range for weights from 600–780 kg (14.34 vs. 13.2–15.0) (Honig et al., 2020), whereas T close to the Retinta cattle range for weights from 466–471 kg (17.18 vs. 17.58–18.38) (Avilés et al., 2015).

The carcass characteristics observed in this study align with Savoia et al. (2019), indicating that the traditional tethered system is significantly disadvantaged compared to loose housing beef production systems. This is evidenced by lower daily carcass gains, delayed slaughter age, and smaller rib eye areas.

Physical activity/exercise enhances the metabolism of working muscles, with the liver responding robustly to meet metabolic demands and supply energy for sustainable exercise. Increased fatty acid oxidation from adipose tissue largely meets the liver's energetic demands. Similar to skeletal muscle and other physiological systems, the liver adapts to repeated exercise demands by enhancing its capacity for fat oxidation. Regular physical activity can protect against and even reverse fatty liver disease, with broad positive health implications, including improved liver metabolic health (Trefts et al., 2015). Additionally, bulls in the L group exhibited

significantly lower perirenal fat weights compared to those in T, while their liver weights were significantly higher, indicating better overall liver metabolic health in L.

Most cold carcass body size characteristics indicated that T bulls exhibited greater bone structure than those in L, consistent with observed relationships between age, bone weight, and hide weight. However, traits such as hind limb perimeter and hind limb meat thickness, indicative of muscling levels, were higher in L than in T, suggesting that physical activity/exercise may improve hind limb musculature among L bulls.

Meat quality

In the statistical model (2), carcass weight fixed factors did not significantly affect meat quality traits alone but influenced some traits through interactions with housing systems or different muscles. Therefore, the effects of housing system and muscle type are emphasized (Table 7).

The pH_{24h} of different muscles was not affected by housing systems ($P>0.05$). However, significant differences in pH_{24h} among muscles were observed ($P<0.01$), with SU>ST>LL. The PL% for SU and ST was influenced by housing systems, being higher in L compared to T ($P<0.01$), while this effect was not significant for LL ($P>0.05$). Additionally, PL% for ST was higher than for LL ($P<0.05$), and results for CL% were consistent with those for PL%.

Shear force in LL and ST was influenced by housing systems, with lower values in L than T ($P<0.05$ or $P<0.01$). Differences in shear force among muscles were significant ($P< 0.05$ or $P<0.01$), with LL>ST>SU. The CIE L* value for ST was affected by housing systems ($P<0.1$), being lower in L than in T. Differences in CIE L* among muscles were also significant ($P<0.01$), with ST>SU>LL. Results for CIE a* and CIE b* were consistent with those for CIE L*. The pH_{24h}, PL%, CL%, shear force, CIE L*, CIE a*, and CIE b* all interacted with housing systems and different muscles ($P<0.01$).

Chemical composition varied by muscle but was not significantly affected by housing systems ($P>0.05$), with variations in water and crude protein content ($P<0.01$). LL had the lowest water content, while SU had the lowest crude protein content. Differences in muscle fiber properties were also observed among muscles ($P<0.01$) (Fig. 4), with key parameters affected by housing systems ($P<0.05$ or $P<0.01$).

Significant variations in meat quality traits among muscles likely stem from differences in anatomical location, contractile and metabolic activity, and myofiber composition (Kim et al., 2016). To achieve optimal sensory quality, different muscle cuts from the same animal may require distinct preparation or cooking techniques (McCarthy et al., 2017). The muscle itself influences tenderness due to its protein content (Picard et al., 2019), and inherent histological differences among bovine muscles play a critical role in meat color (Poveda-Arteaga et al., 2023).

Meat quality traits for ST appear particularly sensitive to housing systems (Fig. 5). As a propulsive and locomotive muscle, ST is more involved in movement than postural muscles and contains a higher proportion of 'white' or fast-glycolytic (FG) muscle fibers responsive to exercise (Pearson, 1990). These fibers can convert to slow-oxidative (SO) or fast-oxidative-glycolytic (FOG) fibers when stimulated with sufficient intensity and duration (López-Bote 2017; Picard and Gagaoua 2020). In contrast, LL comprises primarily postural muscles, while SU is an oxidative 'red' muscle with potentially less susceptibility to physical activity (Ashmore et al., 1972; Vestergaard et al., 2000). Therefore, the effects of physical activity are muscle-specific (Vestergaard et al., 2000).

The pH_{24h} values for both treatments across different muscles fell within the normal range reported by Poveda-Arteaga et al. (2023), which is 5.52–5.77, and did not exceed 5.87, the threshold suggested by Page et al. (2001) for distinguishing between normal and dark-cutting

beef carcasses. Thus, observed differences in pH_{24h} likely have minimal impact on meat quality traits such as color, WHC, tenderness, and texture (Geletu et al., 2021).

Overall rates of CL% for different muscles in both treatments were slightly higher than those reported by Cai et al. (2021) for CL% of three muscle parts 24 h after aging in 30-mon-old XBC: triceps brachii (TB) 32.05%, longissimus dorsi (LD) 27.23%, biceps femoris (BF) 27.85%. The greater water loss in L compared to T may be due to T bulls being four mon older and having more connective tissue, increasing WHC (Gariépy et al., 1999), or the physical activity of bulls in L resulting in a more developed capillary network, decreasing WHC (Dunne et al., 2011).

The shear force value of 6 kg (58.8 N) serves as the threshold between tenderness and toughness (Shackelford et al., 1997). Shear force values for various cuts from L bulls were below 58.8 N, indicating tender meat, while those from T bulls exceeded this value, suggesting tougher meat. Overall shear force values were slightly lower than those reported by Cai et al. (2021) for TB at 7.99 kg (78.30 N), LD at 9.29 kg (91.04 N), and BF at 9.86 kg (96.63 N). The L bulls exhibited more tender meat compared to T bulls, likely because they were slaughtered four months younger and had a faster growth rate (Oddy et al., 2001). Increased physical activity may promote a higher proportion of oxidative muscle fibers, resulting in smaller CSA (Picard and Gagaoua, 2020).

Research over the past two decades indicates that intrinsic factors (ultimate pH, animal age, muscle position, breed, slaughter weight, and sex) and extrinsic factors (production systems, feeding, pre-mortem stress, slaughter season, and chilling rates) significantly influence beef muscle color (Poveda-Arteaga et al., 2023). The meat color values for the two treatments of bulls across different muscles are generally similar to those reported for XBC (Cai et al., 2021), with CIE L* values ranging from 33.71 to 36.79 and CIE a* values from 19.49 to 19.73. The ST muscle in L bulls exhibited a lower CIE a* (less red) and CIE L* (darker) value compared to T

bulls, consistent with findings by Muir et al. (1998) for pasture-fed cattle and Keane and Allen (1998) for extensively reared steers.

There is a common belief that animals raised under 'free-range' or 'extensive' conditions produce darker meat than those raised intensively, attributed to higher levels of exercise promoting myoglobin formation (Dunne et al., 2011; Savoia et al., 2019). Ruling out darker meat due to high ultimate pH (Mahmood et al., 2017), this color may result from elevated pigment levels in the muscle, particularly myoglobin, along with minor contributions from hemoglobin and cytochromes (Dunne et al., 2011). Muscle color depends on both the quantity and quality of myoglobin, including total myoglobin levels and proportions of deoxymyoglobin, oxymyoglobin, and metmyoglobin (Dunne et al., 2011; Poveda-Arteaga et al., 2023). Exercise may increase the proportion of oxidized muscle fibers in the ST of L bulls, enhancing oxidative capacity and mitochondrial activity. This may lead to higher oxygen consumption rates (OCR) at cutting surfaces, which can prevent myoglobin oxygenation during blooming, resulting in reduced red color (Ashmore et al., 1971; Gao et al., 2013).

The water, protein, and fat contents of the different muscles were similar to those reported in other studies (Honig et al. 2020; Geletu et al. 2021). The SU muscle had higher water content, lower protein content, and smaller muscle fiber diameter and CSA compared to the LL muscle, favoring lower shear force values (Picard and Gagaoua 2020), as shown by previous shear force results.

Study limitations and future directions

Lastly, the trials were based on field data analysis, and the results obtained were more in line with actual production and market demands. However, the trial was not designed and controlled from scratch, the initial state of the animals was inconsistent, and the slaughter seasons were also inconsistent. While some errors were dissected and processed using linear mixed procedure, the

interference with the test results was not entirely removed. Additionally, a fast and slow muscle fiber typing test was also originally to have been performed, but ATPase staining was poor, so it did not provide direct evidence to support that physical activity/exercise changes muscle fibers and thus affects meat quality. A variety of tissue samples collected in the trial have been subjected to multi-omics testing, and the molecular mechanisms will be further investigated in conjunction with the results of this study. Overall, this will provide insight into the effects of housing systems on beef cattle production.

Conclusion

The L bulls engaged in nearly twice as much physical activity as the T bulls, leading to better regulation of their muscle metabolic characteristics and mitigating the adverse effects of prolonged lying on animal welfare. They exhibited higher levels of pre-mortem stress and fewer immune responses to allergic and inflammatory processes, as indicated by CBCs. The serum chemistry profile revealed healthier liver and pancreas function, increased muscle damage, and reduced symptoms of acidosis. Despite similar slaughter weights and body size traits, the L bulls were slaughtered approximately four months younger and had a larger eye muscle area. Their lower bone weight resulted in a higher net meat percentage and an improved meat-to-bone ratio. The carcass hind limbs exhibited greater musculature, and the increased liver weight indicated better liver function, while reduced visceral fat contributed to decreased feed waste. Meat quality traits included a darker and less red color, smaller shear force, and reduced muscle fiber diameter. Notably, housing systems had a more significant impact on ST muscles compared to SU and LL muscles. The study also found that in the ranking of factors influencing meat quality, muscle parts > housing systems > carcass weight. In conclusion, loose-housing systems are more advantageous for animal welfare, growth rates, meat yield, and tenderness in XBC compared to tie-stalls.

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Tables and Figures

Table 1. Ingredients and nutrition composition of diets fed in the treatments

Ingredients	composition		DM（%）	Crude nutrients (DM basis,%)[2]					
	Supplied kg/cattle	%（DM）		CP	CF	EE	ASH	Ca	P
Concentrate mix[1]	5.7	≥43.22	≥86	≥15	≤ 15	≤ 5	≤ 12	0.7-1.7	≥0.36
Steam Flaked Corn	0.2	1.59	90	7.64	22	2.6	0.9	0.03	0.16
molasses	0.4	2.75	78	8.50	0.1	0.2	11.3	0.17	0.03
Maize silage	9.5	28.48	34	8.00	21	3.1	5.0	0.28	0.23
straw	1.7	13.64	91	3.00	43	1.8	8.0	0.16	0.05
Stevia rebaudiana dregs	1.0	5.73	65	7.25	88	2.3	8.2	-	-
Potatoes dregs	4.0	4.59	13	6.25	50	0.6	1.0	-	-
Total	22.5	100				-			

[1] The proportions of the commercial feed formula are unclear (Ingredients: Corn, cotton meal, corn husk, rapeseed meal, sunflower meal, baking soda, CaCO3, NaCl, CaHPO3, premix).

[2] DM, dry matter; CP, crude protein; CF, crude fibre; EE, ether extract; ASH, crude ash; Ca, calcium; P, phosphorus;Crude nutrients data from China Feed Database (https://chinafeeddata.org.cn/).

Table 2. Composition of time of day for different levels of physical activity in different housing systems

Physical activity level	Housing systems[1]					
	T n=15	L n=15	SEM	T %day	L %day	p-value
Low-level physical activity (min)	1222^{A}	1032^{B}	19.1	84.86	71.67	<0.001
Medium-level physical activity (min)	212^{B}	352^{A}	14.6	14.72	24.44	<0.001
High-level physical activity (min)	5.61^{B}	55.9^{A}	5.48	0.39	3.89	<0.001

[1] T, tie-stalls; L, loose-housing.

A, B Within a row, means without a common superscript are different (P<0.01).

Table 3. Hematology parameters in different housing systems

Hematology parameter[1]	Housing systems[2]		SEM	p-value	Reference interval
	T n=50	L n=40			
RBC ($\times 10^{12}$L)	8.02	7.88	0.12	0.570	5-10
Hgb (g/dL)	10.7	10.4	0.10	0.212	8-15
HCT (%)	39.6^{α}	38.3^{β}	0.37	0.081	24-46
MCV (fL)	49.3	47.8	0.46	0.103	40-60
MCH (pg)	13.2	13.3	0.12	0.747	11-17
MCHC (g/dL)	27.2^{B}	27.8^{A}	0.10	0.002	30-36
RDW_CV (%)	23.6	23.7	0.17	0.763	-
RDW_SD (fL)	41.6	41.6	0.32	0.910	-
Total WBC ($\times 10^{9}$L)	6.55^{B}	8.29^{A}	0.20	<0.001	4-12
NEU ($\times 10^{9}$L)	3.38^{B}	4.76^{A}	0.15	<0.001	0.6-5.4
EOS ($\times 10^{9}$L)	0.060	0.063	0.003	0.665	0.08-2.4
BAS ($\times 10^{9}$L)	0.021^{A}	0.012^{B}	0.001	<0.001	0-0.25
LYM ($\times 10^{9}$L)	3.07	2.89	0.09	0.331	1.8-9
MON ($\times 10^{9}$L)	0.14	0.15	0.01	0.460	0.08-0.85
NEU%	50.9^{B}	60.4^{A}	1.08	<0.001	15-45
EOS%	0.94^{a}	0.78^{b}	0.04	0.047	2-20
BAS%	0.31^{A}	0.16^{B}	0.02	<0.001	0-2
LYM%	45.1^{A}	36.1^{B}	1.03	<0.001	45-75
MON%	2.19	2.10	0.12	0.717	2-7
PLT ($\times 10^{9}$L)	237^{A}	171^{B}	10.1	<0.001	100-800
MPV (fL)	7.61^{A}	7.09^{B}	0.09	0.004	-
PCT (%)	0.18^{A}	0.11^{B}	0.01	<0.001	-
PDW_CV (%)	35.3^{a}	33.8^{b}	0.33	0.031	-
PDW_SD (fL)	11.9^{a}	10.4^{b}	0.29	0.011	-

[1] RBC, red blood cell; Hgb, hemoglobin; HCT, hematocrit; MCV, mean corpuscular volume; MCH, mean corpuscular hemoglobin; MCHC, mean corpuscular hemoglobin concentration; RDW_CV, RBC distribution width coefficient of variation; RDW_SD, RBC distribution width standard deviation; WBC, white blood cell; NEU, neutrophils; EOS, eosinophils; BAS, basophils; LYM, lymphocytes; MON, monocytes; NEU% = [NEU/WBCs] × 100%; EOS% = [EOS/WBCs] × 100%; BAS% = [BAS/WBCs] × 100%; LYM% = [LYM/WBCs] × 100%; MON% = [MON/WBCs] × 100%; PLT, platelets; MPV, mean platelet volume; PCT = [platelet count × MPV]/10,000; PDW_CV, PLT distribution width coefficient of variation; PDW_SD, PLT distribution width standard deviation.

[2] T, tie-stalls; L, loose-housing.

$^{\alpha, \beta}$ Within a row, means without a common superscript are different ($P<0.1$).

$^{a, b}$ Within a row, means without a common superscript are different ($P<0.05$).

$^{A, B}$ Within a row, means without a common superscript are different ($P<0.01$).

Table 4. Biochemistry parameters in different housing systems

Biochemistry parameter[1]	Housing systems[2]		SEM	p-value	reference interval
	T n=50	L n=40			
TP (g/L)	74.9^{b}	77.4^{a}	0.57	0.028	67.4-74.6
ALB (g/L)	37.3	37.5	0.33	0.776	30.3-35.5
GLOB (g/L)	38.4	39.5	0.62	0.374	30.0-34.8
A/G	0.98	0.95	0.02	0.517	0.84-0.94
TB (umol/L)	1.23	1.69	0.19	0.228	0-27
TBA (umol/L)	14.8	14.1	0.82	0.682	-
GGT (U/L)	21.3$^{\alpha}$	17.9$^{\beta}$	0.87	0.051	6.1-17.4
AST (U/L)	115^{B}	146^{A}	2.96	<0.001	78-132
ALT (U/L)	46.9^{B}	56.3^{A}	2.96	<0.001	11-40
ALP (U/L)	86^{B}	114^{A}	2.99	<0.001	0-488
LDH (U/L)	1218^{B}	1518^{A}	33.37	<0.001	692-1445
AMY (U/L)	341^{A}	247^{B}	14.65	0.001	41-98
LPS (U/L)	28.8^{a}	25.6^{b}	0.69	0.021	-
CK (U/L)	266^{B}	385^{A}	17.36	<0.001	0-350
Crea (umol/L)	141	135	2.41	0.597	44-159
UA (umol/L)	25.7$^{\alpha}$	20.5$^{\beta}$	1.35	0.055	-
UREA (mmol/L)	4.53$^{\beta}$	4.77$^{\alpha}$	0.06	0.064	3-13
U/C	32.2	33.3	0.71	0.453	19-202
GLU (mmol/L)	3.95^{A}	2.95^{B}	0.16	0.001	2-5.6
TC (mmol/L)	2.70$^{\beta}$	2.95$^{\alpha}$	0.08	0.095	1.6-5
TG (mmol/L) [3]	<0.30	<0.30	-	-	-
tCO_2 (mmol/L)	21.7	21.2	0.21	0.177	21.2-32.2
Ca (mmol/L)	2.32^{A}	2.19^{B}	0.01	<0.001	1.5-2.4
PHOS (mmol/L)	2.30	2.35	0.03	0.379	0.81-2.19

[1] TP, total proteins; ALB, albumin; GLOB, globulin; A/G, the ratio of albumin to globulin; TB, total bilirubin; TBA, total bile acids; GGT, gamma-glutamyl transferase; AST, aspartate transaminase; ALT, alanine aminotransferase; ALP, alkaline phosphatase; LDH, lactate dehydrogenase; AMY, amylase; LPS, lipase; CK, creatine kinase; Crea, creatinine; UA, uric acid; UREA, urea; U/C, the ratio of uric acid to creatinine; GLU, glucose; TC, total cholesterol; TG, triglyceride; tCO2, total carbon dioxide; Ca, calcium; PHOS, phosphorus.

[2] T, tie-stalls; L, loose-housing.

[3] TG below instrumental detection limit.

[α, β] Within a row, means without a common superscript are different (P<0.1).

[a, b] Within a row, means without a common superscript are different (P<0.05).

[A, B] Within a row, means without a common superscript are different (P<0.01).

Table 5. Live animal traits in different housing systems.

Live animal traits[1]	Housing systems[2]		SEM	p-value[3]		
	T n=61	L n=58		H	W	H×W
Body weight (kg)	682	679	6.52	0.818	-	-
Chest girth (cm)	215	213	0.66	0.407	<0.001	0.963
Wither height (cm)	136	132	0.46	0.970	<0.001	0.023
Stature (cm)	179	177	0.88	0.993	<0.001	0.600
Hip width (cm)	52.8	54.1	0.31	0.185	<0.001	0.563
UREA (cm^2)	86.2^{β}	91.0^{α}	1.25	0.097	0.009	0.252
ULT (cm)	6.73	7.04	0.09	0.278	0.029	0.352
UFT (cm)	1.63	2.22	0.06	0.508	0.010	0.126
UIMF (%)	9.29^{α}	5.94^{β}	0.43	0.067	0.196	0.365

[1] UREA, ultrasonic rib eye area; ULT, ultrasonic longissimus thoracis thickness; UFT, ultrasonic subcutaneous fat thickness; UIMF, ultrasonic intramuscular fat content or marbling.

[2] T, tie-stalls; L, loose-housing.

[3] H, Housing systems; W, body weight.

$^{\alpha, \beta}$ Within a row, means without a common superscript are different (P<0.1).

Table 6 . Carcass characteristics, organ weight and cold carcass body size traits in different housing systems.

Traits[1]	Housing systems[2]		SEM	p-value[3]		
	T n=61	L n=58		H	W	H×W
Carcass characteristics						
Hot carcass weight (kg)	396.1	393.8	4.19	0.747	<0.001	0.853
Dressing percentage (%)	58.97	58.80	0.18	0.921	0.224	0.948
Net meat weight (kg)	329.0	345.6	4.15	0.370	<0.001	0.730
Net meat percentage (%)	49.03^{β}	50.75^{α}	0.21	0.088	0.964	0.637
Bone weight (kg)	66.86^{A}	55.86^{B}	0.93	0.003	<0.001	0.662
Bone percentage (%)	17.18^{A}	14.34^{B}	0.20	<0.001	0.075	0.246
Meat-to-bone ratio	4.89^{A}	5.97^{B}	0.08	<0.001	0.056	0.578
REA (cm^2)	88.16	91.72	1.31	0.116	0.011	0.281
FT (cm)	0.53	0.88	0.04	0.787	0.182	0.008
Organ weight						
head (kg)	30.06	25.97	0.36	0.353	<0.001	0.005
hide (kg)	37.44^{a}	36.85^{b}	0.49	0.025	<0.001	<0.001
Front hoofs (kg)	5.77	5.55	0.06	0.579	<0.001	0.132
Hing hoofs (kg)	6.03	5.71	0.06	0.784	<0.001	0.084
Heart (kg)	2.55	2.72	0.03	0.465	<0.001	0.558
Liver (kg)	6.51^{B}	7.91^{A}	0.12	<0.001	<0.001	0.033
Spleen (kg)	1.18	1.11	0.02	0.652	0.005	0.802
Lungs (kg)	3.61	3.66	0.04	0.899	<0.001	0.640
Kidney and perirenal fat (kg)	18.01^{a}	11.43^{b}	0.51	0.013	0.012	0.514
Rumen and reticulum (kg)	11.85	11.67	0.15	0.214	<0.001	0.187
Cold carcass body size traits						
Carcass length (cm)	159.97^{A}	147.48^{B}	0.87	0.003	<0.001	0.948
Carcass depth (cm)	79.17^{a}	72.68^{b}	0.48	0.012	<0.001	0.631
Hind limb length (cm)	85.11	84.79	0.31	0.800	<0.001	0.605
Hind limb width (cm)	51.48^{α}	49.94^{β}	0.30	0.072	<0.001	0.140
Hind limb perimeter (cm)	90.78	97.68	0.99	0.166	0.006	0.675
Hind limb meat thickness (cm)	19.10^{b}	22.26^{a}	0.25	0.038	0.029	0.563
Between ribs meat thickness (cm)	6.39^{α}	5.90^{β}	0.09	0.091	<0.001	0.523

[1] REA, rib eye area; FT, subcutaneous fat thickness.

[2] T, tie-stalls; L, loose-housing.

[3] H, Housing systems; W, body weight.

$^{\alpha, \beta}$ Within a row, means without a common superscript are different (P<0.1).

$^{a, b}$ Within a row, means without a common superscript are different (P<0.05).

$^{A, B}$ Within a row, means without a common superscript are different (P<0.01).

Table 7. Meat quality traits, muscle chemical composition and myofiber properties in different housing systems

Traits [1]	Different muscles[2]						SEM	p-value[3]		
	SU		LL		ST			H	M	H×M
	T n=61	L n=58	T n=61	L n=58	T n=61	L n=58				
Meat quality traits										
pH_{24}	5.78	5.69	5.51	5.55	5.63	5.57	0.01	0.102	<0.001	<0.001
	5.73^{A}		5.53^{C}		5.60^{B}					
Pressure loss (%)	36.66^{B}	40.01^{A}	37.71	37.39	36.60^{B}	41.09^{A}	0.18	0.001	0.028	<0.001
	38.33^{ab}		37.55^{b}		38.84^{a}					
Cooking loss (%)	30.54^{B}	34.93^{A}	30.24	30.51	32.05^{B}	36.59^{A}	0.23	0.005	<0.001	<0.001
	32.73^{B}		30.37^{C}		34.32^{A}					
Shear force (N)	60.14	47.67	89.71^{A}	49.09^{B}	71.01^{a}	47.41^{b}	1.26	<0.001	<0.001	<0.001
	53.90^{Bb}		69.39^{A}		59.21^{Ba}					
CIE L*	31.02	28.64	28.31	28.49	35.07^{α}	30.67^{β}	0.20	0.068	<0.001	<0.001
	29.83^{B}		28.39^{C}		32.87^{A}					
CIE a*	19.06	16.73	16.03	15.75	23.86^{A}	18.71^{B}	0.19	0.031	<0.001	<0.001
	17.89^{B}		15.89^{C}		21.28^{A}					
CIE b*	4.98	4.37	5.18	4.24	8.38^{A}	5.56^{B}	0.10	0.009	<0.001	<0.001
	4.67^{B}		4.71^{B}		6.97^{A}					
Chemical composition	T n=10	L n=10	T n=10	L n=10	T n=10	L n=10				
Water (%)	73.78	74.39	71.07	71.46	72.77	73.77	0.22	0.054	<0.001	0.694
	74.09^{A}		71.26^{B}		73.27^{A}					
CP (%)	22.57	23.42	25.17	25.98	24.97	25.07	0.28	0.259	<0.001	0.789
	22.99^{B}		25.58^{A}		25.02^{A}					
EE (%)	1.17	1.17	1.23	1.14	1.23	1.67	0.02	0.295	0.795	0.609
	1.17		1.18		1.20					
Myofibre properties	T n=10	L n=10	T n=10	L n=10	T n=10	L n=10				
Number (n)	31.54^{B}	42.14^{A}	27.28^{B}	38.36^{A}	24.48	27.86	0.65	0.001	<0.001	0.002
	36.84^{A}		32.82^{B}		26.17^{C}					
Diameter (mm)	0.057^{a}	0.051^{b}	0.061^{A}	0.052^{B}	0.066^{a}	0.060^{b}	4.90e-04	<0.001	<0.001	0.006
	0.054^{B}		0.056^{B}		0.063^{A}					
CSA (mm^2)	0.0020	0.0018	0.0024	0.0021	0.0028	0.0027	4.66e-05	0.032	<0.001	0.275
	0.0019^{C}		0.0022^{B}		0.0028^{A}					
Density (n/mm^2)	484.38	537.51	403.39^{β}	485.23^{α}	358.69	406.31	7.76	0.012	<0.001	0.484
	510.94^{A}		444.31^{B}		382.49^{C}					

[1] CP, crude protein; EE, ether extract; CSA, cross-sectional areas.

[2] SU, supraspinatus; LL, longissimus lumborum; ST, semitendinosus; T, tie stalls; L, loose housing.

[3] H, housing systems; M, different muscles.

[α, β] Within a row, means without a common superscript are different (P<0.1).

[a–c] Within a row, means without a common superscript are different (P<0.05).

[A–C] Within a row, means without a common superscript are different (P<0.01).

Fig. 1. Photographs of housing systems. (A) tie-stalls Xinjiang brown cattle. (B) loose-housing Xinjiang brown cattle.

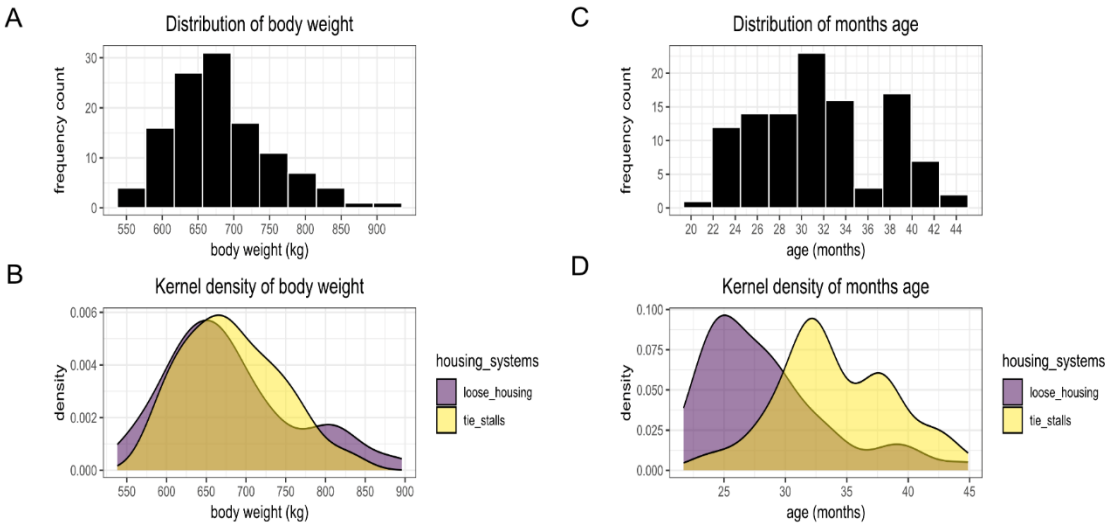

Fig. 2. Frequency count distribution and kernel density plot of body weight and months age for Xinjiang brown cattle. (A) Frequency count distribution of body weight for 119 bulls. (B) Kernel density plot of body weight for 58 loose-housing and 61 tie-stalls bulls. (C) Frequency count distribution of months age for 119 bulls. (D) Kernel density plot of months age for 58 loose-housing and 61 tie-stalls bulls.

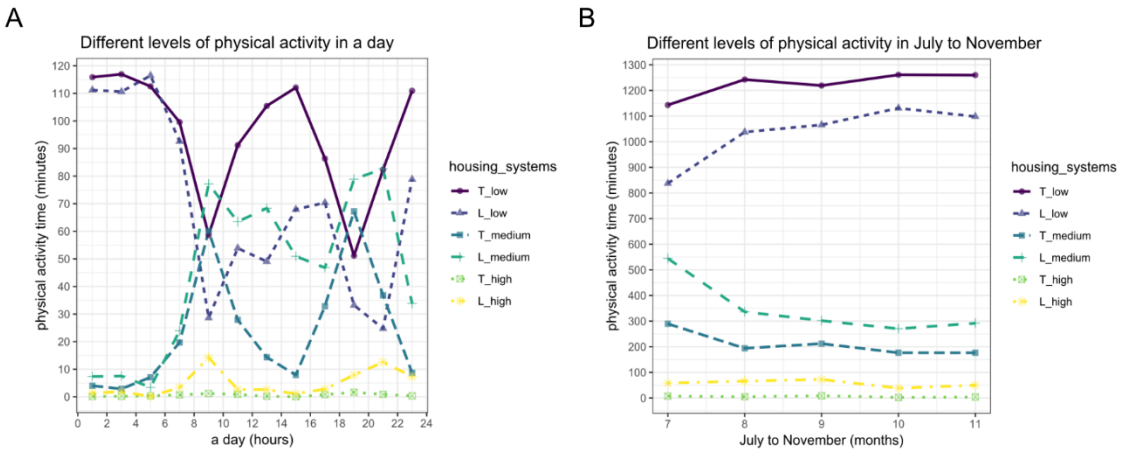

Fig. 3. Different levels of physical activity in housing systems. (A) Different levels of physical activity in a day. (B) Different levels of physical activity in July to November. T_low, tie-stalls group's low levels of physical activity; L_low, loose-housing group's low levels of physical activity; T_medium, tie-stalls group's medium levels of physical activity; L_medium, loose-housing group's medium levels of physical activity; T_high, tie-stalls group's high levels of physical activity; L_high, loose-housing group's high levels of physical activity.

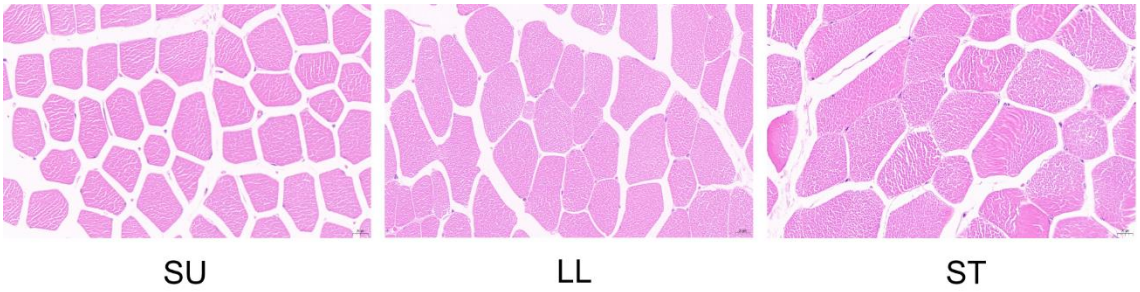

Fig. 4. Hematoxylin and eosin (H&E) staining, bar=20μm. SU, supraspinatus; LL, longissimus lumborum; ST, semitendinosus.

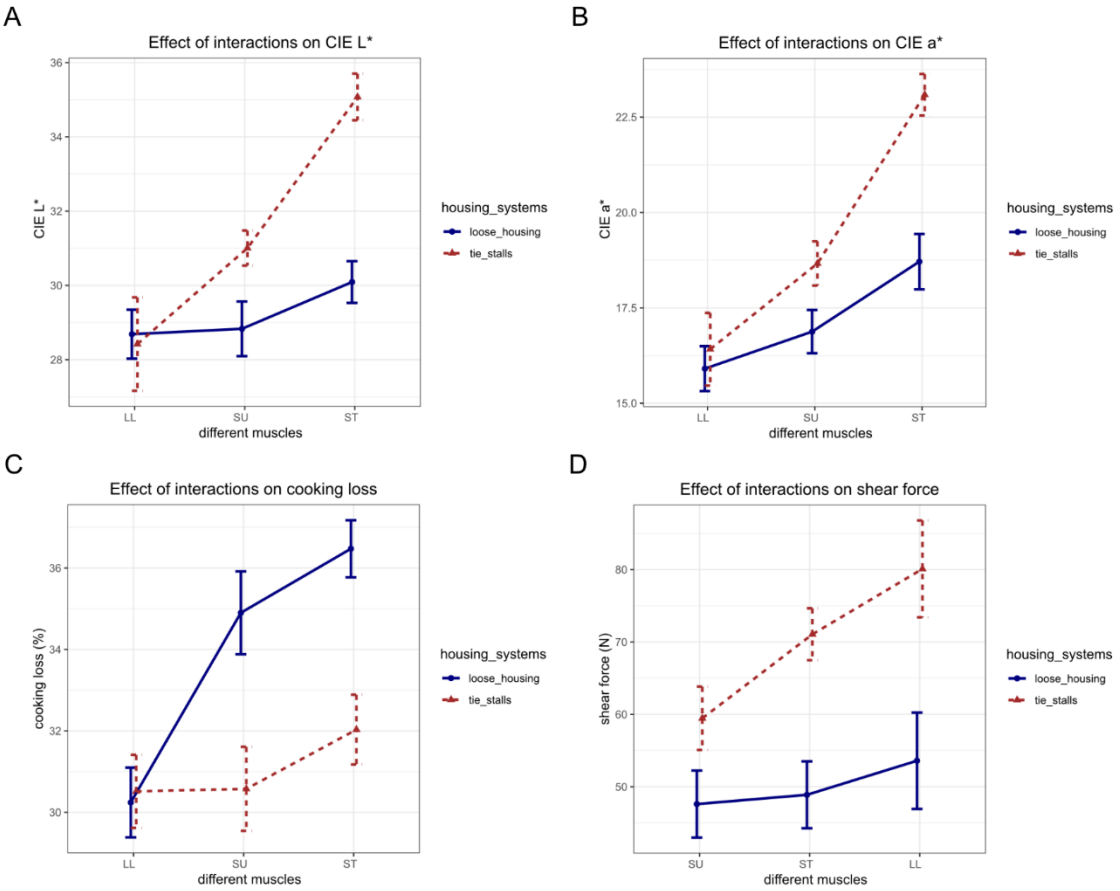

Fig 5. Effects of different muscles interacting with different housing systems on meat quality traits. (A) Effect of interacting on CIE L*. (B) Effect of interacting on CIE a*. (C) Effect of interacting on cooking loss. (D) Effect of interacting on shear force. CIE L*, lightness value; CIE a*, redness value; SU, supraspinatus; LL, longissimus lumborum; ST, semitendinosus.