

Effects of modest early creep feeding on growth, carcass traits, and muscle composition in pasture-raised Wuranke lambs

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Abstract

Early nutritional supplementation may enhance lamb growth in extensive grassland systems, although its effects on carcass traits and muscle composition under low-input pastoral conditions remain unclear. This study examined the effects of modest early creep feeding on growth performance, carcass traits, and *Longissimus dorsi* composition in pasture-raised Wuranke lambs. Forty healthy, uncastrated male singleton lambs were assigned to either a control group (CG; pasture only) or an experimental group (EG; pasture plus creep feed) and monitored from birth until approximately 160 days of age. Creep feed was provided for 50 days, with a low average intake of 52.9 g/lamb/day. Growth traits were measured in all lambs ($n = 20$ per group), whereas carcass evaluation and muscle composition analyses were performed in a subset of eight lambs per group. EG lambs were heavier at the end of supplementation and before slaughter than CG lambs. In the carcass subsample, EG lambs also had greater slaughter weight, hot carcass weight, edible meat weight, and edible meat percentage, whereas the dressing percentage did not differ significantly between groups. The composition of *Longissimus dorsi* muscle was generally similar between groups. After FDR correction, no significant differences in proximate composition, mineral content, fatty acid profile, or amino acid profile were observed. These findings suggest that modest early creep feeding can improve growth and carcass output in this flock of pasture-raised Wuranke lambs, while no major detectable changes in the measured muscle composition occurred. However, because carcass and muscle composition analyses were based on a small subsample, subtle effects cannot be ruled out. Further multi-flock and multi-season studies incorporating direct measurements and economic evaluation are needed before broader practical recommendations can be made.

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1. Introduction

In Inner Mongolia, sheep production relies largely on extensive grazing of native grasslands within low-input pastoral systems (Lin et al. 2012). Under these conditions, pre-weaning lamb growth depends mainly on maternal milk and later increasingly on the quantity and nutritive value of grazed pasture as lambs begin to consume herbage (Poli et al. 2020). However, pasture supply and quality are not constant. These vary with climate, plant growth stage, and grazing pressure, and this variation can restrict nutrient intake during periods when lambs are growing rapidly (Müller et al. 2014). In the Xilingol steppe, native vegetation is commonly dominated by *Leymus chinensis* and *Stipa* spp., and their nutritive value changes seasonally (Li et al. 2024b). Thus, even locally adapted lambs may temporarily experience nutritional limitations during early development. Wuranke sheep are an indigenous breed of Inner Mongolia, raised primarily under traditional pastoral conditions in the Xilingol grassland (Wang et al. 2022; National Commission of Livestock and Poultry Genetic Resources 2025). The breed is associated with Abaga Banner, Xilingol League, and has been studied as a local sheep resource under grazing or steppe conditions (Jin et al. 2023; Yun et al. 2023). Wuranke sheep are well adapted to steppe grazing environments, which makes them a useful model for evaluating

feeding strategies that improve productivity without substantially altering pasture-based management. However, most existing evidence on early lamb supplementation comes from intensive or confinement-based systems, often using non-local breeds (de Melo et al. 2017; Karim et al. 2001; Xu et al. 2023). Information from indigenous lambs raised under natural grazing conditions remains limited, particularly where maternal milk and native pasture remain the main dietary sources. For this reason, studying Wuranke lambs is relevant both biologically and practically for local extensive sheep production.

One practical means of addressing this constraint is creep feeding, whereby nursing lambs are given access to supplemental feed while continuing to graze and suckle (Benson 1995; de Melo et al. 2017). Previous studies have shown that creep feeding or other forms of early supplementation can improve growth performance and, in some cases, carcass weight (Karim et al. 2001; Xu et al. 2023). Nonetheless, responses vary with supplementation level, pasture conditions, and the relative contribution of concentrate to the total diet (Rossatti et al. 2019; Wang et al. 2024). Under extensive pastoral conditions, concentrate intake may remain modest because lambs still rely heavily on maternal milk and native pasture. The response to creep feeding in such systems may therefore differ from that observed in intensive or confinement-

based production. From a practical perspective, modest creep feeding may benefit herders if limited concentrate supplementation improves lamb growth or carcass output while fitting within existing grazing management (Alvarez-Rodriguez et al. 2007). Its practical value, however, depends on whether the additional live-weight or carcass gain is sufficient to offset feed, labour, and management costs (Jiménez et al. 2019). This consideration is especially important in low-input pastoral systems, where feeding interventions need to be simple, affordable, and compatible with routine herd management. Therefore, field-based evidence is needed to assess whether low-input early supplementation can produce measurable production benefits under realistic grazing conditions.

Besides growth and carcass performance, it is also important to examine whether early supplementation changes muscle composition. Feeding systems can influence meat composition, particularly lipid composition and fatty acid profile (Popova et al. 2015). Early-life feeding management can alter fatty acid and amino acid profiles under certain conditions, especially in intensive or artificially reared systems (Chai et al. 2018). In grazing systems where supplement intake is modest and pasture remains the principal dietary component, growth improvements may occur without major changes in meat composition (Fernandez-Turren et al. 2020; Ortiz-Heredia et al. 2023). In addition, a prolonged grazing period after supplementation may attenuate or dilute short-term nutritional effects on muscle composition (Monteschio et al. 2018; Sadrarhami et al. 2022). The remaining question is whether modest early creep feeding can improve growth and carcass output in indigenous lambs raised under extensive grassland conditions while maintaining the muscle compositional characteristics associated with pasture-based production. This study evaluated the effects of 50 days of modest early creep feeding on growth performance, carcass traits, and *Longissimus dorsi* composition in pasture-raised Wuranke lambs. It was hypothesized that early supplementation would improve growth and carcass traits, but would not substantially alter the proximate composition measured, mineral content, fatty acid profile, or amino acid composition of the muscle following a subsequent grazing period on native pasture.

2. Materials and Methods

2.1. Ethical approval and animal care

All procedures involving animals were carried out in accordance with institutional guidelines for care and use of animals in research and were approved by the Ethics Committee for the Use of Animals in Experiments, Mongolian University of Life Sciences, Ulaanbaatar, Mongolia (Approval No. VSBMR-2025-005; Dated: 7 January 2025). Animal management followed routine pastoral practice, but handling procedures were kept as calm and consistent as possible to reduce unnecessary stress. During final handling, lambs were transported together with familiar animals, provided with access to water during lairage, and slaughtered at a licensed commercial abattoir under routine local halal slaughter procedures.

2.2. Study site

The study was conducted in Abaga Banner, Xilingol League, Inner Mongolia, China (44°N, 115°E), located on the southern edge of the Mongolian Plateau (Fig. 1). Xilingol is a semi-arid continental steppe region, characterized by cold, windy, and dry conditions, with annual mean temperature commonly around 1–2 °C and precipitation increasing from approximately 150 mm in the northwest to about 400

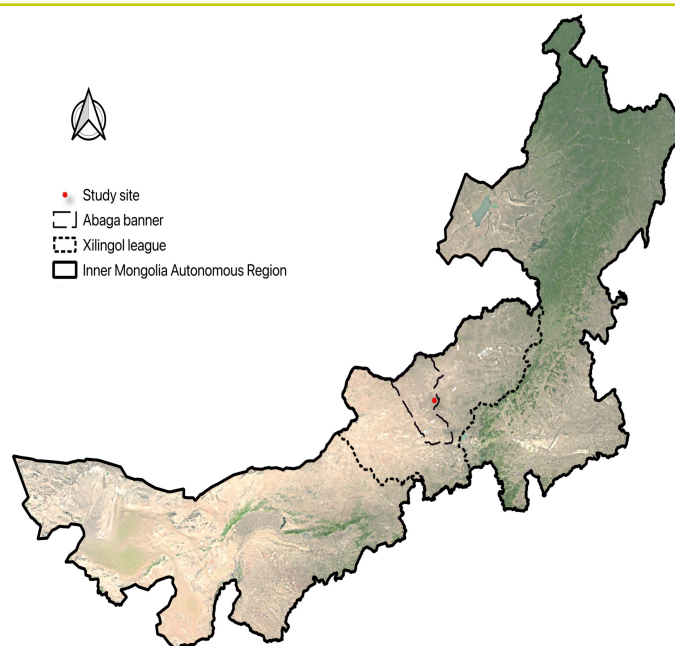


Fig. 1. Location of the study site in Abaga Banner, Xilingol League, Inner Mongolia, China

mm in the southeast of the League (Haiyan and Haimei 2021). Long-term monthly mean temperature and precipitation data used for the study area were obtained from WorldClim 2, which provides gridded climatological normals for 1970–2000 (Fick and Hijmans 2017) and are presented in Fig. 2. The experiment was conducted during the 2025 spring grazing season, following lambing in mid-March. The sheep grazed native temperate steppe pasture representative of the Xilingol region (Li et al. 2024a). To provide seasonal context for the trial, official 2025 climate and grassland monitoring bulletins from the Xilingol League Meteorological Bureau were reviewed. During spring (March–May), which covered lambing and the 50-day supplementation period,

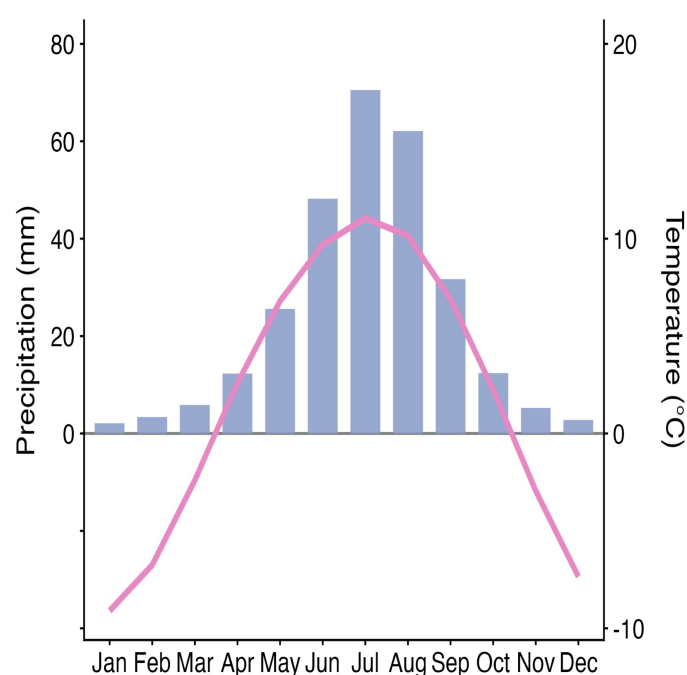


Fig. 2. Long-term monthly mean temperature and precipitation for the study area near Abaga Banner, Inner Mongolia

the league-wide mean temperature was 6.0 °C, 1.0 °C above the long-term average, while mean precipitation was 46.2 mm and close to normal. Compared with the same period in 2024, precipitation in Xilinhot and Abaga Banner was reported to be one to three times higher (Xilingol League Meteorological Bureau 2025).

Grassland monitoring conducted from 22 April to 15 May 2025 showed that natural grassland across Xilingol League had reached the re-greening stage, with generally good re-greening conditions. The League-wide vegetation coverage was 27.6%, and average pasture height was 6.1 cm, representing increases of 6.36 percentage points and 0.8 cm, respectively, compared with the same spring monitoring period of the previous year (Xilingol League Forestry and Grassland Bureau 2025a). Monitoring conducted from 10 to 19 June 2025 further indicated favourable pasture growth, with an average pasture height of 11.58 cm, vegetation coverage of 30.33%, and hay yield of 390.6 kg/ha (26.04 kg/mu), all higher than in the same period of the previous year (Xilingol League Forestry and Grassland Bureau 2025b).

2.3. Animals and experimental design

The study was carried out in a herder-managed flock of approximately 300 sheep, including about 270 breeding ewes. Healthy, uncastrated male singleton Wuranke lambs born within a 15-day lambing period were eligible for inclusion. Lambs were identified from daily lambing records and ear-tagged at birth, and weighed within 24 h after birth. Only singleton lambs were included to reduce variation associated with birth type. The dams were healthy 4- to 5-year-old ewes managed under the same pastoral conditions. A total of 40 lambs were selected and allocated to either a control group (CG; pasture only) or an experimental group (EG; pasture plus creep feed), with 20 lambs in each group. Allocation was performed using stratified randomization based on birth date and birth weight. Lambs were first classified into strata defined by birth-date group (early: born in the first 5 days of the lambing period; late: born in the last 5 days) and birth-weight group (light: below the median birth weight of the selected lambs; heavy: above the median). Within each stratum, random numbers generated in Microsoft Excel were used to assign lambs in a 1:1 ratio to the two groups according to ascending random-number order.

An a priori power analysis (G*Power version 3.1, Heinrich Heine University Düsseldorf, Düsseldorf, Germany) specified final body weight as the primary outcome for sample-size determination. The analysis indicated that 18 lambs per group were required to detect a moderate effect size ($\alpha = 0.05$, power = 80%). However, to account for any possible losses, 20 lambs were allocated to each group. Birth weight was used only for stratified randomization but was not included as a covariate in the main statistical models. This decision was based on the baseline balance between treatment groups and the inclusion of the birth measurement as the first time point in the repeated-measures model. Accordingly, growth trajectories were analysed with group, time and group time interaction as fixed effects, and lamb identity as a random effect.

No lambs died or were excluded after allocation. Therefore, all 40 lambs were included in the growth analyses (CG, $n = 20$; EG, $n = 20$). The individual lamb was the experimental unit for growth, carcass, and muscle composition outcomes. Concentrate intake was recorded at the group level for the EG because lambs had shared access to the creep feeder and individual intake could not be measured. Carcass evaluation and muscle composition analyses were conducted on a structured

subsample of eight lambs per group. These analyses were not included in the a priori power analysis and were considered exploratory. The smaller subsample was used because detailed carcass dissection and laboratory analyses were resource-intensive. To improve representativeness, lambs were selected within each treatment group using a structured approach, the selection procedure is described in Section 2.7. Because these analyses were based on only eight lambs per group, statistical power was limited, and the carcass and muscle composition results were mainly able to detect relatively large between-group differences only.

2.4. Housing and husbandry

Under routine pastoral management, ewe-lamb pairs grazed native pasture during the day within the same general grazing area. Both groups were managed by the same herder and followed the same daily procedures for grazing, watering, animal monitoring, and general husbandry. During the supplementation period, lambs in the CG and EG were maintained in separate but adjacent pens within the same general grazing environment to prevent CG lambs from accessing the creep feed. At night, ewe-lamb pairs were housed in separate adjacent pens without access to pasture. The pens were comparable in general structure, ground surface, shelter, and access to routine husbandry care. Apart from the provision of creep feed to EG lambs and the physical separation required to maintain treatment allocation, management conditions were kept as similar as possible between groups. However, because separate pens were necessary for the feeding treatment, a potential pen or micro-environmental effect could not be completely excluded.

2.5. Feeding management

Both groups remained with their dams and grazed native pasture during the day throughout the experimental period. Lambs in CG received no supplemental concentrate. Lambs in the EG received a commercial pelleted creep feed (Zhengda 585 lamb feed, Charoen Pokphand Groupe, Beijing, China), formulated for early lamb growth. The creep feed was provided in a lamb-only pen excluding ewes for 50 days, from 31 March to 19 May. The feed was offered in a lamb-access-only feeding area before morning turnout, and ewes were excluded from the feeder. According to the manufacturer's label, the main listed ingredients were soybean meal, corn, cottonseed meal, limestone, dicalcium phosphate, sodium chloride, and Zhengda premix. According to the manufacturer's declared composition, the feed contained 18.0% crude protein, $\leq 15.0\%$ crude fibre, $\leq 12.0\%$ crude ash, 0.5-1.5% calcium, $\geq 0.3\%$ total phosphorus, 0.3-2.0% sodium chloride, $\leq 14.0\%$ moisture, and $\geq 0.4\%$ lysine. Metabolizable energy and gross energy were not provided on the label. The concentrate was not independently analysed. During a short adaptation period before the formal supplementation period, creep feed was also tested during the day and at night. Lambs showed little or no intake at those times, probably because they continued to graze during the day and suckle their dams. For this reason, during the formal supplementation period, fresh creep feed was provided only daily in the morning before turnout. Refusals were removed and weighed before new concentrate was supplied. Feed contaminated with soil, bedding, or other foreign material was also removed to maintain feed hygiene and acceptability. Therefore, recorded refusals included both uneaten feed and feed removed for hygiene reasons.

Daily group-level records of concentrate offered, refusals, and

calculated net intake were maintained throughout the 50-day supplementation period. Individual concentrate intake could not be measured because EG lambs shared access to the creep feeder. Across the full supplementation period, EG lambs were offered a total of 107.9 kg creep feed, with 55.0 kg recorded as refusals, resulting in a net group intake of 52.9 kg. This corresponded to an average intake of 52.9 g/lamb/day and a cumulative intake of approximately 2.64 kg/lamb over the supplementation period. Intake increased from 7.2 g/lamb/day during days 1-10 to 90.8 g/lamb/day during days 31-40, before decreasing slightly to 81.9 g/lamb/day during days 41-50 (Table 1). Pasture intake and milk intake were not measured. Therefore, the relative contributions of maternal milk, grazed pasture, and concentrate to total nutrient intake could not be quantified.

2.6. Outcome measures

Growth and body measurements were recorded in all lambs at four time points: T1, within 24 h after birth; T2, at the start of supplementation, at a mean age of 10.7 ± 2.6 d; T3, at the end of the 50-day supplementation period, at a mean age of 60.7 ± 2.6 d; and T4, at the final pre-slaughter measurement, at a mean age of 162.7 ± 2.6 d. T4 was the final body-weight measurement for all lambs. For lambs selected for carcass evaluation, the same T4 live weight measurement was recorded immediately before transport to the abattoir and was used as pre-slaughter live weight in the carcass analysis. Final body weight at T4 was the primary outcome and was used for the a priori power analysis. Secondary outcomes included body weight (BW) trajectory over time, average daily gain (ADG), body length (BL), withers height (WH), heart girth (HG), slaughter weight, hot carcass weight (HCW), dressing percentage, edible meat weight and edible meat proportion. Exploratory outcomes included non-carcass

component weights and *Longissimus dorsi* composition variables, including proximate composition, mineral content, fatty-acid profile, and amino acid profiles.

2.7. Slaughter procedures and carcass evaluation

At approximately 160 days of age, lambs were weighed to obtain final body weight. For lambs selected for carcass evaluation, this measurement was used as pre-slaughter live weight. The selected lambs were then transported to a licensed commercial abattoir in Xilinhot, located approximately 160 km from the study site. Transport began at about 12:00 h, and lambs arrived at the abattoir at about 15:00 h. To reduce transport-related stress, lambs from both treatment groups were transported together under the same conditions, handled calmly during loading and unloading, and kept with familiar animals during transport and lairage. Upon arrival, the animals were held in lairage with free access to water and fasted for approximately 18 h before slaughter the following morning; water remained available throughout the fasting period.

Slaughter was carried out on 31 August 2025 at the licensed commercial abattoir under routine local halal procedures. Although lambs from both treatment groups were transported together, slaughter followed the routine abattoir sequence, with EG lambs processed first followed by CG lambs. Individual identity was maintained using ear-tag number throughout slaughter and postmortem data collection. Hot carcass weight (HCW) was recorded within 45 min of exsanguination. In this study, HCW excluded the tail fat, kidney and pelvic fat, and testicles. Dressing percentage was calculated as HCW divided by pre-slaughter live weight and multiplied by 100. Non-carcass components, including the skin, head, feet, tripe, gut, pluck, kidney and pelvic fat, tail fat, and testicles, were weighed individually. Pluck was defined as the heart, lungs, and liver. For carcass dissection and muscle composition analyses, eight lambs per treatment group were selected at slaughter using a structured subsampling approach described in Section 2.3. Briefly, the subsample within each group included the two heaviest lambs, the two lightest lambs, and four lambs whose pre-slaughter body weights were closest to the group mean. Representativeness was assessed by descriptively comparing the baseline and pre-slaughter body weights of the selected lambs with those of the full treatment groups. Similar means and overlapping ranges were observed at both time points (Table 2).

Table 1. Supplemental concentrate intake in experimental lambs during the 50-day creep-feeding period	
Variable	Experimental group
Supplementation duration (d)	50
Total concentrate offered (kg)	107.9
Total concentrate refusals (kg)	55.0
Total concentrate intake (kg)	52.9
Average concentrate intake (g/lamb/day)	52.9
Cumulative concentrate intake (kg/lamb)	2.64
Days 1-10 intake (g/lamb/day)	7.2
Days 11-20 intake (g/lamb/day)	22.8
Days 21-30 intake (g/lamb/day)	61.8
Days 31-40 intake (g/lamb/day)	90.8
Days 41-50 intake (g/lamb/day)	81.9
Note: Intake was recorded at the group level because experimental lambs shared access to the creep feeder. Daily net intake was calculated as feed offered minus refusals. Recorded refusals included uneaten feed and feed removed for hygiene reasons when contaminated with soil, bedding, or other foreign material. Individual concentrate intake, milk intake, and pasture intake were not measured. Full daily intake records are provided in Table S1	

Table 2. Comparison of baseline and pre-slaughter body weight (kg) between the full treatment groups and the structured carcass subsample			
Group	Time point	Full group (n = 20)	Subset (n = 8)
CG	Baseline	4.56 ± 0.36 (4.0-5.4)	4.56 ± 0.28 (4.0-5.0)
CG	Pre-slaughter	39.72 ± 1.84 (35.9-42.4)	39.99 ± 2.32 (35.9-42.4)
EG	Baseline	4.58 ± 0.32 (4.0-5.3)	4.68 ± 0.32 (4.4-5.3)
EG	Pre-slaughter	43.11 ± 2.72 (39.5-47.5)	43.14 ± 2.88 (39.5-47.5)
Note: Values are mean ± SD (range). EG, experimental group; CG, control group. The subsample comprised the two heaviest, two lightest, and four median-weight lambs per group. Baseline weight was recorded at birth; pre-slaughter weight was recorded at approximately 160 days of age			

Carcasses were dissected by a trained operator. Edible meat was defined as the dissected edible carcass portion remaining after separation from bone and removal of non-edible tissues. Bone, skin, viscera, head, feet, tail fat, major connective tissue, and visible separable fat were excluded. Small amounts of associated edible fat that could not be practically separated from lean tissue during manual dissection were included. Therefore, edible meat in this study mainly refers to the lean edible carcass portion, with unavoidable associated edible fat. After carcass evaluation, both left and right *Longissimus dorsi* muscles were removed from each selected carcass for chemical analysis, as described in Section 2.8.

2.8. Muscle sampling and chemical analysis

Lambs were slaughtered on 31 August 2025, and *Longissimus dorsi* samples were collected on the same day. The *Longissimus dorsi* muscles from both sides of the carcass were removed in full. After trimming external fat and connective tissue, the left and right muscles were pooled to form a single sample of approximately 1 kg per lamb for laboratory analysis. The two sides were therefore not analysed separately. Before chemical analysis, each pooled sample was minced and thoroughly mixed by the analytical laboratory to obtain a homogeneous composite sample. Samples were vacuum-packed and stored at -20°C in a deep freezer at the slaughterhouse within 2 h after sampling. They were stored at -20°C until transport on 9 September 2025. Frozen samples were transported from Xilinhot to Hohhot in insulated foam boxes containing ice packs, with a transport time of approximately 10 h. The samples remained fully frozen upon arrival and were received by the laboratory on 9 September 2025, with their condition recorded as normal and intact. No freeze–thaw cycle occurred before laboratory receipt. Laboratory analyses were conducted between 9 and 19 September 2025.

Samples were analysed by Pony Testing International Group (Shanghai, China), an ISO/IEC 17025-accredited laboratory. Proximate composition, minerals, fatty acids, and amino acids were determined using Chinese National Standard (GB) methods. Results for proximate composition, minerals, fatty acids, and amino acids are reported on a fresh-weight basis unless otherwise stated. Moisture, protein, fat, ash, and energy were determined using the following methods: moisture (GB 5009.3-2016, Method 1), ash (GB 5009.4-2016, Method 1), protein (GB 5009.5-2025, Method 1) (National Health Commission of the People's Republic of China 2025), fat (GB 5009.6-2016, Method 2), and energy (GB 28050-2011). Fatty acids were analysed according to GB 5009.168-2016 (Method 2) (National Health and Family Planning Commission of the People's Republic of China 2016a). Mineral concentrations were measured as follows: zinc (GB 5009.14-2017), iron (GB 5009.90-2016), magnesium (GB 5009.241-2017), and sodium (GB 5009.91-2017). Amino acids were determined according to GB 5009.124-2016 (National Health and Family Planning Commission of the People's Republic of China 2016b). Detailed assay information is provided in the Supplementary Materials (Table S1). For individual fatty acids, especially minor long-chain fatty acids, some values were reported by the laboratory as not detected. Compound-specific limits of detection or quantification were not provided in the laboratory report. Therefore, ND was defined as not detected or below the laboratory reporting limit. Fatty acids reported as ND in one or both groups were not included in between-group statistical comparisons.

2.9. Blinding

Complete blinding was not feasible for live animal management, growth measurement, morphometric measurement, slaughter selection, or carcass processing because lambs were managed under field conditions according to their assigned treatment groups. Accordingly, routine animal care, growth measurements, slaughter selection, and carcass dissection were performed by investigators who were aware of treatment assignment. Carcass evaluation was also not fully blinded. Although butchers and carcass-processing operators were not informed of treatment allocation, the investigator responsible for collecting and recording carcass data was aware of group allocation. This was necessary to maintain animal identity and group order throughout slaughter and dissection and to avoid carcass or sample mix-ups, especially after skin removal. To reduce potential measurement and observer bias, the same standardized procedures, anatomical landmarks, weighing methods, and trained personnel were used consistently for all lambs. Nevertheless, the lack of complete blinding may have introduced a risk of measurement or observer bias, particularly for morphometric and carcass-related outcomes. By contrast, laboratory analyses of muscle composition were conducted blind to group allocation via anonymized sample codes before submission to the testing laboratory, and analysts were unaware of the treatment origin of each sample.

2.10. Animal care and monitoring

Throughout the experimental period, the herder and investigators monitored the animals daily for general health, normal suckling and grazing behaviour, appetite, mobility, and general condition. Feed hygiene and pen sanitation were checked regularly to maintain concentrate acceptability and reduce contamination by soil, bedding, or other foreign material. Concentrate offered and refusals in the EG were recorded daily (Supplementary Dataset S1). Lambs in both treatment groups received the same routine health management. As part of preventive flock health management, all lambs received sheep pox vaccination on 5 April 2025. Lambs did not receive albendazole suspension or other antiparasitic treatment during the experimental period. Ewes received albendazole suspension on 20 April 2025 at approximately 0.10–0.15 mL/kg body weight according to routine farm practice. In April 2025, ewes also received routine preventive vaccination against ovine clostridial diseases, including sheep pulpy kidney disease, sudden death syndrome, and enterotoxaemia, as well as foot-and-mouth disease vaccination. In July, after the supplementation period, the flock received external parasite control using a pour-on or spray-wash treatment as part of routine seasonal management. No disease outbreak, morbidity, mortality, adverse events, or treatment-requiring health problems were observed in either lamb group during the trial. No predefined humane endpoint was reached.

2.11. Statistical analysis

All statistical analyses were performed using R (version 4.5.2, R Foundation for Statistical Computing, Vienna, Austria). Tests were two-sided, and statistical significance was set at $p < 0.05$ unless otherwise stated. Repeated measurements of BW, WH, BL, and HG were analysed using linear mixed-effects models fitted with the (lmerTest) package. The models included treatment group (CG vs. EG), time point (T1, T2, T3, and T4), and their interaction as fixed effects, with lamb identity included as a random intercept to account for repeated measurements within animals. Time was treated as a categorical factor. Denominator degrees of freedom were estimated using the Kenward-Roger

approximation. When the group $\times$ time interaction was significant, pairwise comparisons between groups at each time point were conducted (emmeans) with Bonferroni adjustment for multiple comparisons. Estimated marginal means (EMMs) and standard errors (SEs) are reported for each group $\times$ time combination.

The model was specified as:

$$Y_{ijk} = \mu + G_i + T_j + (G \times T)_{ij} + L_k + \varepsilon_{ijk}$$

where i denotes treatment group, j denotes time point, and k denotes lamb (random effect); Y_{ijk} is the observed trait value, μ is the overall mean, G_i is the fixed effect of group, T_j is the fixed effect of time, $(G \times T)_{ij}$ is the group $\times$ time interaction, L_k is the random effect of lamb, and ε_{ijk} is the residual error.

Birth weight was used for stratified randomization but was not included as a covariate in the primary repeated-measures models because baseline body weight was comparable between groups and T1 was included in the longitudinal model. ADG, carcass traits, and non-carcass components were analysed as endpoint outcomes. Normality within each group was assessed using the Shapiro-Wilk test, and homogeneity of variance was assessed using Levene's test. Variables that met parametric assumptions were compared between groups using independent-samples t -tests; Welch's t -test was used when variances were unequal. Variables that did not meet these assumptions were analysed using the Mann-Whitney U test. Effect sizes were reported as Hedges' g for parametric comparisons and rank-biserial correlation for non-parametric comparisons. Data are presented as mean $\pm$ SD or median (interquartile range), as appropriate.

Growth, morphometric, carcass, and non-carcass variables were treated as pre-specified outcome domains and were not subjected to a single global multiple-testing correction. These outcomes were interpreted with consideration of effect size, confidence intervals, biological relevance, and consistency across related traits. Muscle composition analyses were considered exploratory because they were conducted on a smaller subsample and included multiple proximate, mineral, fatty-acid, and amino-acid variables. Therefore, Benjamini-Hochberg false discovery rate (FDR) correction was applied separately within predefined outcome families. An FDR-adjusted threshold of $q <$

0.05 was used for interpretation. Both unadjusted p -values and FDR-adjusted q -values are reported in the Supporting Information (Table S2-S6). For analytes reported as not detected or below the laboratory reporting limit, between-group comparisons were not performed when valid numerical values were unavailable in one or both groups.

3. Results

3.1. Growth traits over time

Growth traits of lambs in the control group (CG) and experimental group (EG) across the four measurement time points are presented in Table 3, and the corresponding growth trajectories are shown in Fig. 3. Linear mixed-effects models showed significant effects of time for all traits ($p < 0.001$). Significant group $\times$ time interactions were detected for body weight (BW, $F = 18.119$, $p < 0.001$), withers height (WH, $F = 8.685$, $p < 0.001$), body length (BL, $F = 2.904$, $p = 0.0379$), and heart girth (HG, $F = 4.638$, $p = 0.0043$), indicating that growth trajectories differed between treatments over time. For BW, there was a significant main effect of group ($F = 11.645$, $p = 0.0015$). At T1 and T2, BW was similar between groups. However, by T3, EG lambs were 1.31 kg heavier than CG lambs, corresponding to a 6.5% greater BW (21.59 vs. 20.27 kg; post-hoc $p = 0.0031$). At T4, EG lambs were 3.37 kg heavier than CG lambs, corresponding to an 8.5% higher final BW (43.10 vs. 39.72 kg; post-hoc $p < 0.001$). For WH, the main effect of group was not significant ($F = 1.770$, $p = 0.1913$), but the group $\times$ time interaction was significant. WH was similar between groups at T1 and T2, whereas EG lambs had 1.89 cm greater WH than CG lambs at T3, corresponding to a 3.5% difference (55.5 vs. 53.8 cm; post-hoc $p < 0.001$). At T4, the difference was 1.39 cm, corresponding to a 2.1% difference (66.8 vs. 65.6 cm; post-hoc $p = 0.0064$).

For BL, no significant main effect of group was observed ($F = 1.560$, $p = 0.2193$), although the group $\times$ time interaction was significant ($F = 2.904$, $p = 0.0379$). BL was similar between groups at earlier time points. At T3, EG lambs had a small, non-significant numerical advantage of 1.35 cm, corresponding to a 2.5% difference (54.4 vs. 53.0 cm; post-hoc $p = 0.0530$). At T4, EG lambs had 1.50 cm greater BL than CG lambs, corresponding to a 2.3% difference (65.7 vs. 64.2 cm; post-hoc $p = 0.0319$). Because the absolute differences were small and the overall

Table 3. Estimated marginal means ($\pm$ SE) for growth traits in Wuranke lambs from the control and experimental groups across time points, with fixed effects from linear mixed-effects models

Trait	Group	Time point				Fixed effects (F , p)		
		T1	T2	T3	T4	Group	Time	Group $\times$ Time
BW (kg)	CG	4.55 $\pm$ 0.33	6.87 $\pm$ 0.33	20.27 $\pm$ 0.33 ^b	39.72 $\pm$ 0.33 ^b	11.645, 0.0015	7889.35, < 0.001	18.119, < 0.001
	EG	4.58 $\pm$ 0.33	6.75 $\pm$ 0.33	21.59 $\pm$ 0.33 ^a	43.10 $\pm$ 0.33 ^a			
WH (cm)	CG	38.4 $\pm$ 0.38	41.5 $\pm$ 0.38	53.8 $\pm$ 0.38 ^b	65.6 $\pm$ 0.38 ^b	1.770, 0.1913	4089.74, < 0.001	8.685, < 0.001
	EG	38.5 $\pm$ 0.38	40.6 $\pm$ 0.38	55.5 $\pm$ 0.38 ^a	66.8 $\pm$ 0.38 ^a			
BL (cm)	CG	30.5 $\pm$ 0.49	37.6 $\pm$ 0.49	53.0 $\pm$ 0.49	64.2 $\pm$ 0.49 ^b	1.560, 0.2193	2561.21, < 0.001	2.904, 0.0379
	EG	30.6 $\pm$ 0.49	37.0 $\pm$ 0.49	54.4 $\pm$ 0.49	65.7 $\pm$ 0.49 ^a			
HG (cm)	CG	39.8 $\pm$ 0.53	48.3 $\pm$ 0.53	64.4 $\pm$ 0.53 ^b	87.4 $\pm$ 0.53 ^b	4.757, 0.0354	4129.39, < 0.001	4.638, 0.0043
	EG	39.9 $\pm$ 0.53	47.9 $\pm$ 0.53	66.2 $\pm$ 0.53 ^a	90.0 $\pm$ 0.53 ^a			

Note: BW, body weight; WH, withers height; BL, body length; HG, heart girth; CG, control group; EG, experimental group. Values are estimated marginal means $\pm$ SE ($n = 20$ per group). Mixed-model fixed effects included group, time, and the group $\times$ time interaction. Within the same trait and time point, values with different superscript letters differ significantly between groups (Bonferroni-adjusted $p < 0.05$). Absence of superscript letters indicates no significant between-group difference. For BL, only T4 showed a significant difference between groups ($p = 0.0335$), whereas T3 did not ($p = 0.0553$).

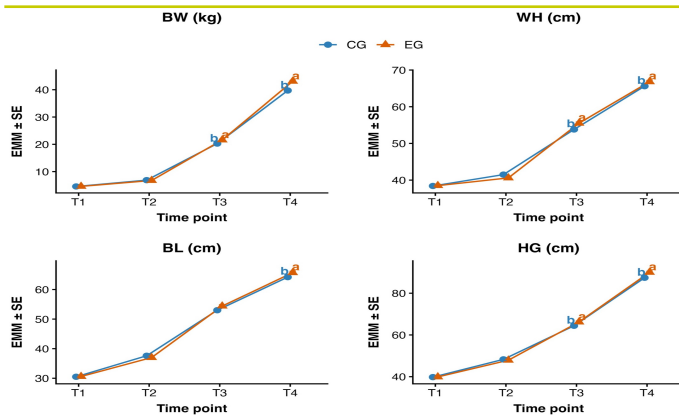


Fig. 3. Growth performance and body measurements of Wuranke lambs in the control and experimental groups from birth to pre-slaughter age

group effect was not significant, the biological importance of the BL response is uncertain. For HG, both the main effect of group ($F = 4.757$, $p = 0.0354$) and the group $\times$ time interaction ($F = 4.638$, $p = 0.0043$) were significant. HG was similar between groups at T1 and T2. At T3, EG lambs had 1.83 cm greater HG than CG lambs, corresponding to a 2.8% difference (66.2 vs. 64.4 cm; post-hoc $p = 0.0139$). At T4, the difference increased to 2.58 cm, corresponding to a 3.0% higher HG in EG lambs (90.0 vs. 87.4 cm; post-hoc $p < 0.001$). Overall, early creep feeding altered growth trajectories, with the clearest treatment-related differences observed for BW and HG. Differences in WH and BL were statistically detectable at some later time points but were small in absolute and relative terms; therefore, these morphometric findings should be interpreted cautiously.

3.2. Average daily gain

Average daily gain (ADG) across the defined growth intervals is presented in Table 4. The T1–T2 interval represents the pre-supplementation period, T2–T3 corresponds to the 50-day supplementation period, and T3–T4 represents the post-supplementation grazing period after creep feeding had ended. During the pre-supplementation interval from T1 to T2, ADG did not differ significantly between groups, although mean ADG was numerically lower in EG than in CG (200.17 vs. 223.76 g/d; $p = 0.262$). From T2 to T3, EG lambs showed higher ADG than CG lambs (296.90 vs. 267.90 g/d; $p < 0.001$), representing an absolute increase of 29.0 g/day, or approximately 10.8% relative to CG. This advantage persisted from T3 to T4, where EG lambs also had higher ADG than CG lambs (210.88 vs.

190.74 g/d; $p < 0.001$), corresponding to an absolute difference of 20.14 g/day, or approximately 10.6% relative to CG. Because creep feeding had already ended during this interval, this difference should be interpreted as a maintained growth advantage rather than a direct effect of ongoing concentrate intake.

Across the overall growth period, cumulative ADG was also higher in EG from T1 to T4 (236.88 vs. 216.30 g/d; $p < 0.001$) and from T2 to T4 (239.18 vs. 216.12 g/d; $p < 0.001$). The corresponding absolute differences were 20.57 g/day for T1 to T4 and 23.06 g/day for T2 to T4, equivalent to 9.5% and 10.7% increases relative to CG, respectively. Effect sizes were small for T1–T2 but large for all subsequent intervals. Overall, the ADG results indicate that EG lambs grew faster during the supplementation period and maintained a higher growth rate during the subsequent grazing period. However, because milk and pasture intakes were not measured, the relative contribution of concentrate intake to these differences could not be quantified.

3.3. Slaughter, carcass traits and non-carcass components

Slaughter and carcass traits are presented in Table 5 and Fig. S1. Because carcass evaluation was based on a limited subsample, these results should be interpreted cautiously. EG lambs had greater slaughter weight than CG lambs (43.14 vs. 39.99 kg; $p = 0.030$), consistent with the higher final live weight observed in the growth analysis. Hot carcass weight was also higher in EG than in CG (19.55 vs. 18.34 kg; $p = 0.038$), corresponding to an absolute difference of 1.21 kg, or approximately 6.6% relative to CG. Edible meat weight was also higher in EG than in CG (12.90 vs. 11.38 kg; $p = 0.029$), with an absolute difference of 1.52 kg, or approximately 13.4% relative to CG. These findings indicate that the greater pre-slaughter live weight of EG lambs was reflected in higher carcass and edible meat output. Dressing percentage did not differ significantly between groups ($p = 0.184$). Therefore, the present results do not provide clear evidence that early creep feeding improved carcass yield relative to slaughter weight. EG lambs had a greater proportion of edible meat in the carcass than CG lambs (66.36% vs. 64.58%; $p = 0.038$), but this result should be interpreted cautiously because of the small subsample size and the p -value close to 0.05. In contrast, bone proportion, bone weight, and the edible meat-to-bone ratio did not differ significantly between groups ($p > 0.05$).

Non-carcass component weights are presented in Table S2. Briefly, EG lambs had greater head weight, feet, and pluck weight than CG lambs. No significant between-group differences were observed for skin, tripe, gut, kidney and pelvic fat, tail or testicle weights ($p > 0.05$).

Table 4. Average daily gain (ADG; g/d) of Wuranke lambs from the control and experimental groups over different growth intervals

Interval	CG (n = 20)	EG (n = 20)	<i>p</i> -value	Hedges' <i>g</i>
T1–T2	223.76 $\pm$ 81.98	200.17 $\pm$ 42.29	0.262 [†]	-0.36 (-0.98, 0.27)
T2–T3	267.90 $\pm$ 24.34	296.90 $\pm$ 22.27	< 0.001	1.24 (0.56, 1.92)
T3–T4	190.74 $\pm$ 11.73	210.88 $\pm$ 21.43	< 0.001 [†]	1.17 (0.49, 1.83)
T1–T4	216.30 $\pm$ 11.62	236.88 $\pm$ 16.85	< 0.001	1.42 (0.72, 2.11)
T2–T4	216.12 $\pm$ 10.53	239.18 $\pm$ 17.04	< 0.001 [†]	1.63 (0.90, 2.34)

Note: Values are mean $\pm$ SD. ADG, average daily gain; CG, control group; EG, experimental group. Effect sizes are expressed as Hedges' *g* with 95% confidence intervals. T1–T2, birth to start of supplementation; T2–T3, supplementation period; T3–T4, end of supplementation to pre-slaughter; T1–T4, overall study period; T2–T4, start of supplementation to pre-slaughter. [†] *p*-value from Welch's *t*-test

Table 5. Slaughter weight and carcass traits of Wuranke lambs from the control and experimental groups

Trait	CG (n = 8)	EG (n = 8)	p-value	Effect size (95% CI)
Slaughter weight (kg)	39.99 ± 2.32	43.14 ± 2.88	0.030	1.20 (0.11, 2.26)
Hot carcass weight (kg)	18.34 (16.08–18.56)	19.55 (17.53–20.81)	0.038	0.63 (0.15, 0.87) †
Dressing percentage (%)	44.02 ± 1.25	44.91 ± 1.29	0.184	0.70 (-0.33, 1.70)
Edible meat (% of HCW)	64.58 ± 1.19	66.36 ± 1.85	0.038	1.15 (0.06, 2.19)
Bone (% of HCW)	23.76 ± 1.08	22.81 ± 1.49	0.167	-0.73 (-1.73, 0.30)
Edible meat (kg)	11.38 ± 0.88	12.90 ± 1.54	0.029	1.22 (0.12, 2.28)
Bone (kg)	4.18 ± 0.21	4.41 ± 0.24	0.058	1.03 (-0.03, 2.07)
Edible meat-to-bone ratio	2.72 ± 0.16	2.92 ± 0.26	0.087	0.92 (-0.13, 1.94)

Note: Values are presented as mean ± SD or median (IQR), as appropriate. HCW, hot carcass weight; CG, control group; EG, experimental group. p-values were obtained using the independent-samples t-test or Mann–Whitney U test. Effect sizes are presented as Hedges' g with 95% confidence intervals (CI) for parametric comparisons and as rank-biserial correlation with 95% confidence intervals for nonparametric comparisons (†). Edible meat refers to the dissected edible carcass portion, remaining after separation from bone and removal of non-edible tissues, excluding tail fat; small amounts of unavoidable associated edible fat were included

Because these traits were examined as secondary component outcomes and several related non-carcass variables were tested without formal multiple-testing correction, the differences in head, feet, and pluck weights should be interpreted cautiously. These differences may partly reflect the greater overall body size of EG lambs rather than specific treatment effects on individual non-carcass organs or tissues. Overall, modest early creep feeding was associated with greater slaughter weight, hot carcass weight, and edible meat weight in the carcass subsample. However, because dressing percentage and most carcass composition indicators did not differ significantly, the carcass response is best interpreted as increased body size and meat output rather than clear evidence of improved carcass yield or carcass conversion efficiency.

3.4. Summary composition traits of the *Longissimus dorsi* muscle

Summary composition traits of the *Longissimus dorsi* muscle are presented in Table 6, and corresponding effect sizes with 95% confidence intervals are shown in Fig. 4. After false discovery rate (FDR) correction, no significant between-group differences were observed for proximate composition, including moisture, protein, fat, ash, or energy content. Among the mineral variables, Fe concentration was lower in EG than in CG (0.88 ± 0.11 vs. 1.10 ± 0.23 mg/100 g, respectively); the difference was significant before correction but not after FDR adjustment (raw $p = 0.030$, $q = 0.121$), and was therefore treated as a chance finding. No significant between-group differences were detected for fatty acid summary variables, including SFA, MUFA, PUFA, the PUFA/SFA ratio, and the $n-6/n-3$ ratio, or for amino acid summary variables, including total AA, total EAA, and the EAA/total AA ratio, after FDR correction.

Individual fatty acid and amino acid results are provided in Table S5 and Table S6, respectively. No individual fatty acid remained significantly different between EG and CG after FDR correction (all $q > 0.05$). Several fatty acids showed nominal unadjusted differences, including C17:0, C18:0, C20:0, C20:3n6, C20:5n3, and C22:1n9, but none remained significant after adjustment for multiple testing. Fatty acids consistently below the detection limit were recorded as zero or below the laboratory reporting limit in both groups and were not interpreted

as treatment-related differences. Overall, early creep feeding did not produce major detectable changes in the summary chemical composition of the *Longissimus dorsi* muscle at slaughter. Because muscle composition was evaluated in a small subsample of lambs, the absence of FDR-significant differences should be interpreted as absence of major detectable effects rather than evidence that no biological effect occurred.

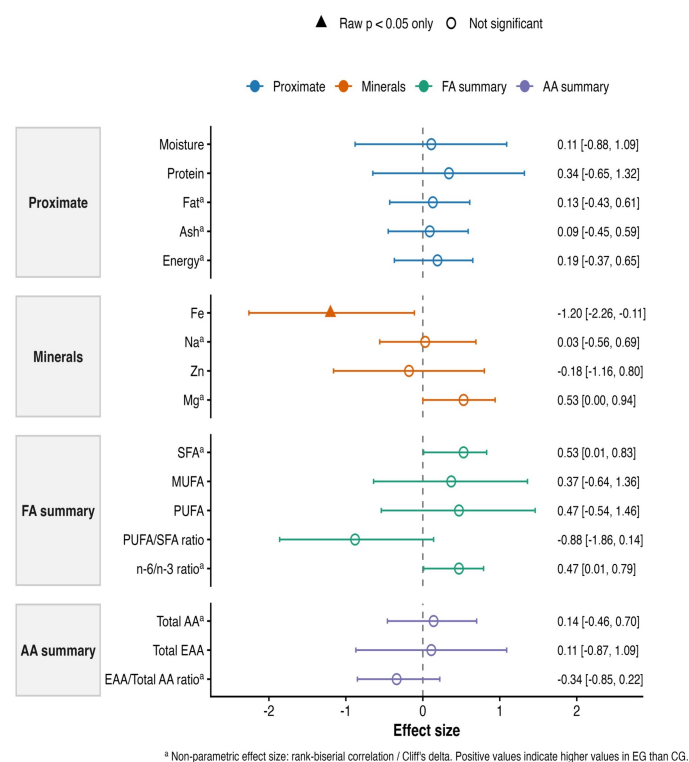


Fig. 4. Effect sizes for summary composition traits of the *Longissimus dorsi* muscle in pasture-raised Wuranke lambs

Table 6. Summary composition traits of the *Longissimus dorsi* muscle of Wuranke lambs from the control and experimental groups

Variable	CG (n = 8)	EG (n = 8)	Raw <i>p</i>	FDR <i>q</i>	Effect size (95% CI)
Proximate composition					
Moisture (g/100 g)	74.20 ± 1.88	74.35 ± 0.66	0.834	0.834	0.11 (-0.88, 1.09)
Protein (g/100 g)	20.28 ± 0.68	20.54 ± 0.85	0.506	0.834	0.34 (-0.65, 1.32)
Fat (g/100 g)	3.10 (2.73–6.53)	3.85 (2.83–4.80)	0.721	0.834	0.13 (-0.43, 0.61) ⁺
Ash (g/100 g)	1.00 (0.98–1.10)	1.05 (0.97–1.10)	0.798	0.834	0.09 (-0.45, 0.59) ⁺
Energy (kJ/100 g)	470 (446–581)	493 (461–516)	0.574	0.834	0.19 (-0.37, 0.65) ⁺
Minerals					
Fe (mg/100 g)	1.10 ± 0.23	0.88 ± 0.11	0.030	0.121	-1.20 (-2.26, -0.11)
Na (mg/100 g)	55.60 (54.25–61.40)	56.75 (54.28–58.30)	0.959	0.959	0.03 (-0.56, 0.69) ⁺
Zn (mg/100 g)	2.48 ± 0.26	2.42 ± 0.40	0.713	0.939	-0.18 (-1.16, 0.80)
Mg (mg/100 g)	20.80 (19.70–21.40)	21.50 (21.05–21.80)	0.083	0.373	0.53 (0.00, 0.94) ⁺
Fatty acid summary variables					
SFA (g/100 g)	0.95 (0.66–1.33)	1.65 (1.10–1.98)	0.083	0.224	0.53 (0.01, 0.83)
MUFA (g/100 g)	0.97 ± 0.63	1.20 ± 0.51	0.442	0.619	0.37 (-0.64, 1.36)
PUFA (g/100 g)	0.167 ± 0.041	0.184 ± 0.025	0.334	0.619	0.47 (-0.54, 1.46)
PUFA/SFA ratio	0.167 ± 0.050	0.124 ± 0.043	0.084	0.224	-0.88 (-1.86, 0.14)
n-6/n-3 ratio	2.47 (2.31–2.76)	2.69 (2.57–3.07)	0.130	0.224	0.47 (0.01, 0.79) ⁺
Amino acid summary variables					
Total AA (g/100 g)	17.15 (16.90–18.53)	17.75 (16.78–18.63)	0.721	0.834	0.14 (-0.46, 0.70) ⁺
Total EAA (g/100 g)	8.32 ± 0.43	8.37 ± 0.43	0.824	0.834	0.11 (-0.87, 1.09)
EAA/Total AA ratio	0.477 (0.468–0.481)	0.472 (0.467–0.475)	0.279	0.834	-0.34 (-0.85, 0.22) ⁺

Note: Values are presented as mean ± SD or median (IQR), as appropriate. SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; AA, amino acids; EAA, essential amino acids; CG, control group; EG, experimental group. Raw *p*-values were obtained using the independent-samples *t*-test or Mann-Whitney *U* test. False discovery rate (FDR) correction was applied within each predefined outcome family. Effect sizes are presented as Hedges' *g* with 95% confidence intervals (CI) for parametric comparisons and as rank-biserial correlation with 95% confidence intervals for nonparametric comparisons (⁺)

4. Discussion

This study examined whether a low level of early creep feeding could improve production performance in pasture-raised Wuranke lambs, while providing little evidence of lasting changes in the measured chemical composition of the *Longissimus dorsi* muscle. The clearest response was observed in growth and carcass output. Lambs given access to creep feed were heavier at the end of supplementation and before slaughter, and this advantage was reflected in greater slaughter weight, hot carcass weight, and edible meat weight. By contrast, proximate composition, mineral content, fatty-acid summary traits, and amino-acid summary traits showed no major FDR-confirmed differences between groups. Taken together, the present study provided no robust evidence that early creep feeding at the level used here

produced clear and persistent shifts in the detailed chemical profile of the *Longissimus dorsi* muscle. The improved growth performance observed in supplemented lambs is consistent with previous studies showing that early nutritional supplementation can improve weight gain in grazing lambs (Karim et al. 2001; Xu et al. 2023). In the present study, however, the response should not be interpreted as the effect of concentrate intake alone. Average concentrate consumption was low, approximately 53 g/lamb/day, or 2.64 kg per lamb over the 50-day supplementation period. The growth advantage therefore probably arose from a combination of factors, including access to concentrate, continued milk intake, grazing behaviour, maternal effects, and seasonal pasture conditions. Because individual concentrate intake, milk intake, and pasture intake were not measured, the relative contribution of each factor could not be separated.

Several mechanisms could explain why a small amount of creep feed was associated with better growth. Early exposure to solid feed may help lambs adapt to non-milk nutrient sources and support the transition from suckling to grazing, particularly during a period when nutrient demand is increasing rapidly (Liu et al. 2022; Sun et al. 2018). Creep feeding may also encourage learning of feeding and earlier use of solid feed, which could benefit growth even when the absolute amount of concentrate consumed is modest. However, these explanations remain inferential. Rumen development, individual concentrate intake, milk intake, and pasture intake were not measured, so the present study cannot determine whether the growth response resulted from improved digestive development, greater total nutrient intake, altered grazing behaviour, or differences in maternal milk supply (Hornick et al. 2000; Luzardo et al. 2019; Ryan et al. 1993). The intake record also supports this interpretation: concentrate consumption increased during the supplementation period and then declined slightly in the final stage, when spring vegetation was likely becoming more available. Still, this explanation should be treated cautiously because pasture biomass and nutritive value were not directly measured. The carry-over response therefore appears biologically plausible, but its exact cause cannot be separated from the combined effects of milk intake, pasture conditions, and early concentrate access. The relatively high proportion of refusals also indicates that creep-feed intake was voluntary and limited, especially during the early adaptation period. Therefore, the observed growth response should be interpreted as the effect of access to creep feed within a grazing system, rather than as a response to a fixed or fully consumed concentrate allowance.

The carcass results followed the same general pattern as the growth data. EG lambs had greater slaughter weight, hot carcass weight, and edible meat weight, but dressing percentage did not differ significantly between groups. This indicates that early creep feeding increased carcass output mainly by increasing pre-slaughter live weight, rather than by improving carcass yield as a proportion of body weight (Ekiz et al. 2012; Karim et al. 2001). The slightly higher edible meat proportion in EG may suggest greater tissue accretion, but this result should be interpreted cautiously because the carcass analysis was based on a small subsample and the p-value was close to 0.05. Overall, the practical carcass response appears to be greater meat output per lamb, not a clear change in carcass partitioning or dressing efficiency. Although the carcass results should be viewed as exploratory, their practical relevance lies in the size and persistence of the live-weight and carcass-weight differences under field grazing conditions. Even with low concentrate intake, EG lambs reached a higher slaughter weight and produced heavier carcasses. In an extensive system, where large changes to feeding management may be difficult, this type of response could be meaningful if it can be achieved with a small amount of supplement (Lin et al. 2012; Müller et al. 2014). At the same time, the relatively small carcass subsample used in this study should be taken into consideration while interpreting the precision and generalizability of these estimates.

The measured composition of the *Longissimus dorsi* muscle was largely similar between the control and supplemented lambs. Although a few variables showed nominal unadjusted differences, none remained statistically significant after correction for multiple testing. This overall pattern is broadly consistent with reports from grazing systems in which moderate supplementation improved growth performance but

had limited effects on overall muscle composition (Fernandes et al. 2010; Scarpa et al. 2021). Several factors may help explain the limited compositional response observed. First, concentrate intake was low, averaging approximately 53 g/lamb/day, or 2.64 kg per lamb over the full supplementation period. Second, lambs grazed native pasture for approximately 100 days after supplementation ended, which may have diminished any short-term dietary effects on muscle composition by the time of slaughter (Monteschio et al. 2018; Sadrarhami et al. 2022). Third, lambs remained with their dams throughout the supplementation period, so the concentrate acted as a supplement to milk and pasture intake rather than as a major dietary replacement. Together, these features indicate that the nutritional intervention was modest relative to the overall production system. This interpretation is further supported by the individual fatty acid and amino acid profiles, which showed little evidence of systematic divergence between groups after correction for multiple testing. Although several fatty acids showed nominal unadjusted differences, these patterns were not robust after adjustment and should therefore be interpreted cautiously. Taken together, the present study suggests that early creep feeding at the level used here was insufficient to produce clear and persistent shifts in the detailed chemical profile of the *Longissimus dorsi* muscle.

From a practical perspective, modest early creep feeding may be relevant in extensive grassland systems where lamb growth is constrained by seasonal pasture conditions, variable milk supply, and limited forage quality during early life (Liu et al. 2022). In this study, supplemented lambs achieved higher final live weight and greater hot carcass weight despite consuming only a small amount of concentrate. This suggests that creep feeding acted as a short-term nutritional bridge rather than as a major replacement for milk or pasture. For herders, the value of this strategy depends on whether the added carcass gain offsets the cost of supplementation. As shown in Table S8, the 1.21 kg increase in hot carcass weight in EG lambs, valued at 56 CNY/kg, corresponded to an estimated added carcass value of 67.76 CNY per lamb. In comparison, the direct creep-feed cost was 10.56 CNY per lamb, based on 2.64 kg of concentrate intake and a feed price of 4 CNY/kg. Under these assumptions, the added carcass value was greater than the direct feed cost. However, this is only an illustrative partial comparison, not a full economic evaluation. Labour, feeding facilities, storage, delivery, transport, management time, and market-price variation were not included, although such costs are normally considered in partial-budget evaluation of farm management changes (Dhehibi et al. 2020; Ehui and Rey 1992). Therefore, practical recommendations remain limited. This approach may be applicable to other low-input pastoral systems, including neighbouring Mongolian grassland regions, but its effectiveness and profitability should be confirmed across different breeds, flocks, seasons, pasture conditions, feed prices, and market settings (Suttie et al. 2005).

Several limitations should be considered while interpreting these findings. First, although the sample size was adequate for the primary growth outcome, only eight lambs per group were included in the carcass and muscle composition analyses because these procedures were resource-intensive. Consequently, this reduced the precision of the carcass estimates and limited statistical sensitivity for detecting anything other than relatively large differences in muscle composition. Accordingly, the absence of significant differences after FDR correction should not be interpreted as evidence of no effect or equivalence between groups. Second, individual milk intake, pasture intake, and

total nutrient intake were not measured, and concentrate intake was recorded only at the group level. This limits interpretation of the mechanisms underlying the observed growth response. The improvement in growth cannot be attributed exclusively to the concentrate supplement, because possible variation in milk production, grazing behaviour, pasture intake, or individual willingness to consume creep feed could not be assessed. Third, the study was conducted in a single herder-managed flock during one production season, using one indigenous breed under local management conditions. In addition, site-specific experimental-year weather data, pasture biomass, botanical composition, and pasture nutritive value were not directly measured; instead, regional climate and grassland monitoring data were used to provide environmental context. Therefore, the findings may not be directly generalizable to other flocks, environments, breeds, years, pasture conditions, or feeding systems. Fourth, complete blinding was not feasible during live-animal management or carcass processing, and physical separation of treatment groups was required to prevent control lambs from accessing creep feed. Although standardized measurement procedures were used, potential group-level management, behavioural, or observer effects cannot be fully excluded. Finally, the economic interpretation was limited to a simple comparison of additional carcass value and direct concentrate cost, without accounting for labour, feeding facilities, feed storage, delivery, transport, or market-price variation. Future studies should use multi-flock and multi-season designs, larger carcass and muscle-composition subsamples, direct measurements of milk and pasture intake, individual supplement intake, site-specific pasture quality and quantity, actual meteorological data, and more complete economic evaluation. Formal equivalence or non-inferiority designs would also be useful to better assess whether early creep feeding has no meaningful effect on muscle composition.

5. Conclusions

Under the conditions of this field study, modest early creep feeding improved growth performance and carcass output in pasture-raised Wuranke lambs. Supplemented lambs achieved greater slaughter weight, hot carcass weight, edible meat weight, and edible meat percentage, whereas no major detectable differences were observed in the measured chemical composition of the *Longissimus dorsi* muscle. Therefore, the main response to supplementation appeared to be increased body size and meat output rather than improved carcass yield or altered carcass partitioning. Modest early creep feeding produced little evidence of major changes in muscle composition of the *Longissimus dorsi* muscle at slaughter. Proximate composition, mineral content, fatty-acid summary traits, and amino-acid summary traits showed no FDR-confirmed treatment differences. However, because muscle composition was evaluated in a small subsample, subtle effects cannot be ruled out. These findings suggest that low-level early supplementation may be a promising nutritional strategy for improving lamb productivity under extensive grassland conditions similar to those of the present study. Nevertheless, the results should be interpreted cautiously because the study involved one flock, one production season, group-level rather than individual concentrate intake measurement, no direct milk or pasture intake data, small carcass and muscle-composition subsamples, and no formal economic evaluation. Further multi-flock and multi-season studies with direct intake measurements and economic assessments are needed before broader practical recommendations can be made.

Declarations

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Conflict of interest: The authors declare that they have no conflicts of interest

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Ethics approval: The study was conducted in accordance with national and institutional guidelines for care and use of animals in the research and was approved by the Ethics Committee for the Use of Animals in Experiments, Mongolian University of Life Sciences (approval code: VSBMR-2025-005; approved on 7 January 2025)

Data availability: The data supporting the findings of this study are provided in the Supplementary Materials. Additional underlying data are available from the corresponding author on reasonable request

Supplementary data

The supplementary tables and data set are available on journal website. Click the link to access the supplementary tables and data set ([Supplementary Tables & Data Set](#))

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