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Ruminants

Effects of Different Levels of Dietary Curcumin Nano-Micelles on Nutrient Digestibility, Skeletal Growth Indices, and Faecal Consistency of Suckling Simmental Calves Under Heat Stress Conditions

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ABSTRACT

This study evaluated the effects of dietary curcumin nano-micelles (CNM) on growth performance, nutrient digestibility, skeletal development, and faecal consistency in heat-stressed suckling Simmental calves. Thirty-two male calves (10 days old; 43.7 ± 2.5 kg) were randomly assigned to one of four dietary treatments: CTRL (control), T20, T40, and T80, corresponding to 0, 20, 40, and 80 mg of CNM per calf per day, with eight replicates per group. The trial lasted 45 days, including a 7-day adaptation period. CNM supplementation significantly improved growth performance, with average daily gain (ADG) increasing in T40 and T80 groups (0.31 kg/day) compared to CTRL (0.29 kg/day; $p = 0.029$). Dry matter intake (DMI) was higher in T80 (1.58 kg/day) than CTRL (1.47 kg/day; $p = 0.003$), while feed conversion ratio was unaffected. Nutrient digestibility was generally unchanged, except for neutral detergent fibre (NDF) digestibility, which showed a quadratic response ($p = 0.010$), with the lowest value observed in T40 (22.33%). CNM significantly enhanced skeletal growth: body length ($p = 0.041$), hip height ($p < 0.001$), heart girth ($p = 0.005$), abdominal girth ($p = 0.025$), ankle circumference ($p = 0.006$), pin bone width ($p < 0.001$), hip width ($p = 0.031$), and body depth ($p = 0.012$) increased notably in T40 and T80 groups over time. Faecal consistency remained stable ($p = 0.964$), indicating no negative effects on intestinal health over time. These findings demonstrate that CNM supplementation can improve feed intake and promote skeletal development in heat-stressed calves, potentially enhancing resilience under thermal stress. Further research is warranted to optimise CNM dosing for sustainable ruminant production.

1 | Introduction

Heat stress is a critical challenge in livestock production, particularly in regions with high ambient temperatures and humidity (Bokharaeian et al. 2024a). Cattle are susceptible to heat stress, which negatively affects feed intake, nutrient utilisation, growth performance and overall health (Muzzo et al. 2025). Heat stress induces physiological and metabolic changes, leading to oxidative stress, reduced immune function, and impaired skeletal growth (Cantet et al. 2021; Wang et al. 2019). Furthermore, compromised gut integrity and altered microbial populations in the gastrointestinal tract due to heat stress can result in poor nutrient digestibility and faecal inconsistency, further exacerbating production inefficiencies (Bokharaeian et al. 2024b). Addressing these challenges is essential to improve the resilience of cattle under heat stress conditions. One promising nutritional strategy to mitigate heat stress-induced growth retardation and digestive inefficiencies is the inclusion of bioactive compounds with antioxidant and anti-inflammatory properties in animal diets (Bokharaeian et al. 2023a). Curcumin, a polyphenolic compound derived from turmeric (*Curcuma longa*), has gained attention due to its strong antioxidant, anti-inflammatory, and gut-protective effects (Amalraj et al. 2017). However, conventional curcumin has poor bioavailability due to its hydrophobic nature and rapid metabolism. To overcome these limitations, nano-micelle technology has been developed, enhancing the solubility, absorption, and bioavailability of curcumin in the digestive tract (Hatamipour et al. 2019). Dietary supplementation with curcumin nano-micelles (CNM) has been shown to enhance nutrient digestion, strengthen antioxidant defence mechanisms, support growth performance, and preserve meat quality during storage in heat-stressed animals (Bokharaeian et al. 2025a; Bokharaeian et al. 2025b).

Previous studies have highlighted the beneficial effects of curcumin supplementation on various aspects of ruminant health and performance. For instance, curcumin has been shown to improve feed efficiency, enhance intestinal barrier function, and modulate the gut microbiome in heat-stressed animals (Bokharaeian et al. 2023b; Szymanski et al. 2018). However, research on the effects of CNM supplementation specifically in heat-stressed cattle remains limited.

In light of the existing knowledge gaps, this study hypothesises that dietary supplementation with different levels of CNM will improve nutrient digestibility, enhance skeletal growth indices, and promote better faecal consistency in cattle under heat stress conditions. Therefore, the primary aim of this study was to evaluate the effects of increasing levels of dietary CNM on nutrient digestibility, skeletal growth parameters, and faecal consistency in cattle under heat stress conditions. The findings from this study provide valuable insights into the potential application of CNM as a dietary intervention to enhance resilience and productivity in livestock under heat stress conditions.

2 | Materials and Methods

2.1 | Ethical Considerations

All the experimental procedures mentioned in the present study were approved by the Animal Welfare and Ethics Committee of the Faculty of Animal Science at the Gorgan University of Agricultural Sciences and Natural Resources (Gorgan, Iran).

2.2 | Animal Management and Experimental Design

The present study was conducted on a private farm in Gorgan, Iran, over a 45-day period spanning August and September 2023. The trial included a 7-day adaptation period. Thirty-two Simmental calves (average birth weight: 43.7 ± 2.5 kg) were separated from their dams immediately after birth, weighed, and placed in individual standard pens of 1.2 × 2.4 m. Each stall was equipped with straw bedding for comfort and hygiene, which was cleaned and replaced daily. At birth, umbilical cords were disinfected with iodine tincture and subsequently treated every 6 h for the first two days. During the first two days, colostrum was provided at 10% of the calves' body weight to ensure passive immunity transfer. From the third day onwards, whole milk was introduced, and weaning was completed by day 56. On the third day, calves were randomly allocated to one of four experimental treatments in a completely randomised design, with eight calves per treatment: CTRL (control, basal diet with no additives), T20 (basal diet + 20 mg CNM per calf per day), T40 (basal diet + 40 mg CNM per calf per day) and T80 (basal diet + 80 mg CNM per calf per day). CNM (purchased from Exir Nano Sina Company, Tehran, Iran) was administered as a solution mixed with the morning milk feeding to ensure precise dosing. Throughout the lactation period, calves were fed whole milk at 10% of their body weight, divided into two equal daily feedings. A starter feed, formulated with an 80:20 concentrate-to-alfalfa ratio, was provided every morning at 8:00 am. Fresh water was available ad libitum. The composition of the experimental concentrate is presented in Table 1.

TABLE 1 | Feed ingredients and nutritional composition of the experimental diet.

Items	Values
Ingredients, %DM	
Alfalfa, hay	20.0
Barley, grain	24.0
Corn, grain	22.4
Soybean meal	12.8
Rapeseed meal	10.4
Wheat bran	8.00
Premix*	0.96
Sodium bicarbonate	0.80
Salt	0.64
Nutrient Composition	
Dry matter, %	89.20
Crude protein, % DM	18.40
Ether extract, % DM	2.24
Neutral detergent fibre, % DM	26.08
Acid detergent fibre, % DM	8.16
Ash, % DM	4.71
Metabolisable energy, Mcal/kg	2.69

*Contained per kilogram of the premix: 1,000,000 IU of vitamin A, 250,000 IU of vitamin D3, 3000 IU of vitamin E, 32,000 mg of magnesium, 10,000 mg of manganese, 10,000 mg of zinc, 300 mg of copper, 100 mg of selenium, 100 mg of calcium, 3000 mg of iron, 100 mg of cobalt, 30,000 mg of phosphorus and 100 mg of antioxidants.

2.3 | Growth Performance

Calf growth performance was assessed by recording body weight at the beginning of the study and subsequently at two-week intervals before the morning feeding. Body weight estimates were obtained using a commercial weight tape, which correlates thoracic girth to body weight (Reis et al. 2008). During each measurement, calves were positioned in a stable quadrupedal stance with their heads facing forward to ensure consistency. Daily dry matter intake (DMI) was determined by measuring the difference between the feed offered and the feed refused over a 24-h period for each calf. If feed refusals remained below 200 g for three consecutive days, the following day's feed allowance was increased by 10%. This feeding adjustment protocol was maintained throughout the study to meet the calves' nutritional demands. The collected data were then used to calculate average daily gain (ADG) and feed conversion ratio (FCR) for each calf, providing key indicators of growth performance and feed efficiency.

2.4 | Temperature-Humidity Index

Heat stress severity was evaluated based on ambient temperature and relative humidity, expressed as the Temperature-Humidity Index (THI). Ambient temperature and relative humidity were recorded every 60 minutes using a temperature-humidity data logger (Hatol, 2060NX, CMOSens Technology, Bani Electronic System Co., Iran), positioned in the pen area at the height of the calves' heads to ensure accurate environmental monitoring. The THI was calculated using the equation proposed by NASEM (2021) as follows:

$$\mathrm{THI} = (1.8 \times \mathrm{T}^{\circ}\mathrm{C} + 32) - [(0.55 - 0.0055 \times \mathrm{RH}) \times (1.8 \times \mathrm{T}^{\circ}\mathrm{C} - 26)]$$

The ambient temperature (T°C) was measured in Celsius, and RH was represented as the percentage of relative humidity. According to Armstrong (1994), the THI values were classified as follows: THI < 72 was considered to indicate no heat stress, THI between 72 and 78 was classified as moderate heat stress (MHS), THI between 79 and 89 was identified as severe heat stress (SHS), and THI ≥ 90 was classified as extreme severe heat stress (ESHS).

2.5 | Apparent Digestibility of Nutrients

Apparent digestibility of dietary nutrients was assessed by collecting feed and faecal samples over the final five days of the experiment, utilising acid-insoluble ash (AIA) as an internal marker. Faecal samples were obtained daily from the rectum, pooled, homogenised, and a 100 g composite sample per calf was stored at −20°C until analysis (Fombelle et al. 2003). Before analysis, dried samples were ground through a 1-mm sieve.

2.6 | Chemical Analysis

Feed and faecal samples were analysed according to AOAC (2005) procedures. Dry matter (DM) was determined using method 930.15, crude protein (CP) using method 976.05, ether extract (EE) using method 920.39, and ash using method 942.05. Neutral detergent fibre (NDF) and acid detergent fibre (ADF) concentrations were measured following the method proposed by Van Soest et al. (1991), omitting sodium sulphite and α-amylase.

2.7 | Skeletal Indicators

Skeletal growth in calves was evaluated by measuring multiple parameters, including body length, withers height, hip height, heart girth, abdominal girth, ankle circumference, forelimb circumference, pin bone width, hip width, body depth, chest width, and rump width. Measurements were recorded at both the beginning and end of the study, following the methodology outlined by Rajabpour et al. (2024).

2.8 | Faecal Consistency Score

To assess the apparent consistency of faeces throughout the experimental period, daily visual evaluation of faecal appearance was performed. Faecal consistency scoring was used as a health indicator and recorded daily for each calf. Scoring was conducted according to the method described by Heinrichs et al. (2005). Based on this method, faeces were scored as follows: firm and well-formed (score 1), firm but unformed (score 2), normal (score 3), loose (score 4), and watery with blood (score 5).

2.9 | Statistical Analysis

Statistical analyses were performed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Growth performance, feed efficiency, skeletal growth indicators, and faecal consistency scores were analysed as repeated measures using the PROC MIXED procedure, accounting for time and treatment interactions. Nutrient digestibility data were analysed using PROC GLM, assuming a completely randomised design with four treatments and eight replicates per treatment. Linear and quadratic model p-values were determined using polynomial contrasts to assess trends across treatments. Data are presented as least-squares means, and Tukey's multiple range test was used to determine significant differences. Statistical significance was set at $p < 0.05$.

3 | Results

3.1 | Climatic Conditions

Figure 1 illustrates the average daily and hourly THI throughout the study period. Over time, the THI exhibited a decreasing trend but remained predominantly within the moderate heat stress zone, with an average value of 74.1 ± 4.70. Between 07:00 and 12:00 and again from 17:00 to 21:00, the THI stayed within the moderate heat stress range, whereas from 13:00 to 16:00, it rose into the severe heat stress zone, highlighting the substantial thermal challenge faced by the calves. Heat stress negatively impacts ruminant productivity, particularly in growing calves, by impairing feed intake, nutrient utilisation, and physiological homeostasis (Chauhan et al. 2023).

3.2 | Growth Performance

Table 2 presents the effects of different levels of dietary CNM on the growth performance of calves under heat stress conditions. ADG was significantly influenced by dietary CNM levels

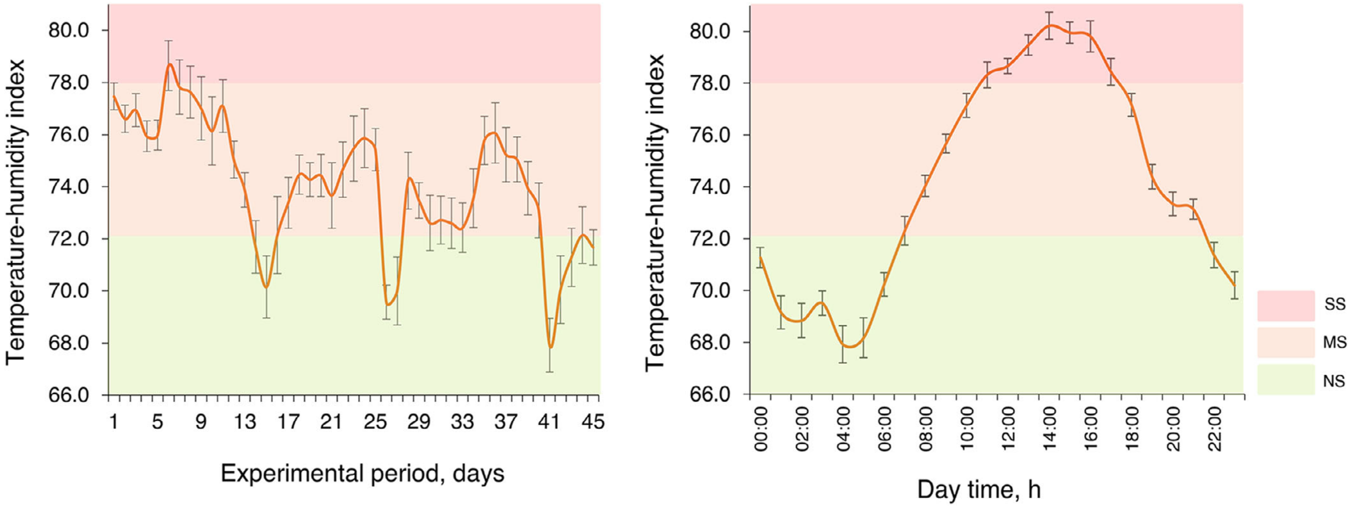

FIGURE 1 | Average daily and hourly Temperature-Humidity Index (THI) recorded throughout the experimental period. THI classifications include extreme severe heat stress (ESHS), severe heat stress (SHS), and the thermoneutral (TN) zone.

TABLE 2 | Effects of different levels of dietary CNM on the growth performance of suckling calves under heat stress conditions ($n = 8$).

Performance	Treatments*				SEM[3]	p-value[4]	
	CTRL	T20	T40	T80		Trt.	Trt. × Time
Live weight, kg	51.35	53.42	52.60	53.61	0.435	0.258	0.025
Average daily gain, kg	0.29	0.28	0.31	0.31	0.004	0.029	0.037
Weight gain, kg	4.30	4.25	4.63	4.63	0.057	0.029	0.036
Average DMI[1], kg/day	1.47	1.55	1.57	1.58	1.544	0.003	< 0.001
Average FCR[2]	5.08	5.40	5.02	5.10	0.072	0.236	0.127

*CTRL, T20, T40 and T80 represents supplementation of CNM at 0, 20, 40 and 80 mg/day/animal, respectively; [1] Average dry matter intakes (diet + milk); [2] Feed conversion ratio; [3] standard error of the means; [4] Trt. and Trt. × Time represents *p*-values for the effect of treatments and treatment × Time interaction, respectively.

($p = 0.029$), with a notable interaction with time ($p = 0.037$). Similarly, total weight gain was affected by CNM supplementation ($p = 0.029$), with a significant time interaction ($p = 0.036$). Furthermore, DMI was significantly influenced by dietary CNM levels ($p = 0.003$), with a strong interaction with time ($p < 0.002$), suggesting a time-dependent response to CNM supplementation. However, FCR remained unaffected by both dietary CNM levels ($p = 0.236$) and its interaction with time ($p = 0.127$), indicating that while CNM influenced growth performance and intake patterns, it did not significantly alter feed efficiency under heat stress conditions.

3.3 | Nutrient Digestibility

Table 3 presents the effects of different levels of dietary CNM on the apparent nutrient digestibility in calves under heat stress conditions. CNM supplementation exhibited a quadratic effect ($p = 0.010$) on NDF digestibility, with the highest digestibility observed in calves supplemented with 40 mg of CNM ($p = 0.021$). However, CNM supplementation did not significantly influence the digestibility of dry matter, organic matter, crude protein, or ether extract ($p > 0.05$).

3.4 | Skeletal Growth Indices

Figure 2 illustrates the effects of increasing levels of dietary CNM on the skeletal growth indices of suckling calves under heat stress conditions. CNM supplementation significantly influenced body length ($p = 0.034$), with a significant treatment × time interaction ($p = 0.041$), indicating varying responses over time among experimental groups. Similarly, CNM supplementation significantly affected withers height ($p = 0.025$), while a significant treatment × time interaction ($p = 0.104$) was not observed. Hip height tended to respond to CNM supplementation ($p = 0.073$), with a significant treatment × time interaction ($p < 0.001$), reflecting differential growth patterns across treatment groups. Heart girth was significantly influenced by CNM supplementation ($p = 0.009$), with a significant treatment × time interaction ($p = 0.005$) reflecting dynamic changes over time. Abdominal girth showed a highly significant response to CNM supplementation ($p < 0.001$), along with a significant treatment × time interaction ($p = 0.025$). Ankle circumference was also significantly affected by CNM supplementation ($p = 0.018$), with a significant treatment × time interaction ($p = 0.006$). Forelimb circumference responded significantly to CNM supplementation ($p = 0.005$), with a tendency toward a treatment × time interaction ($p = 0.060$). Pin

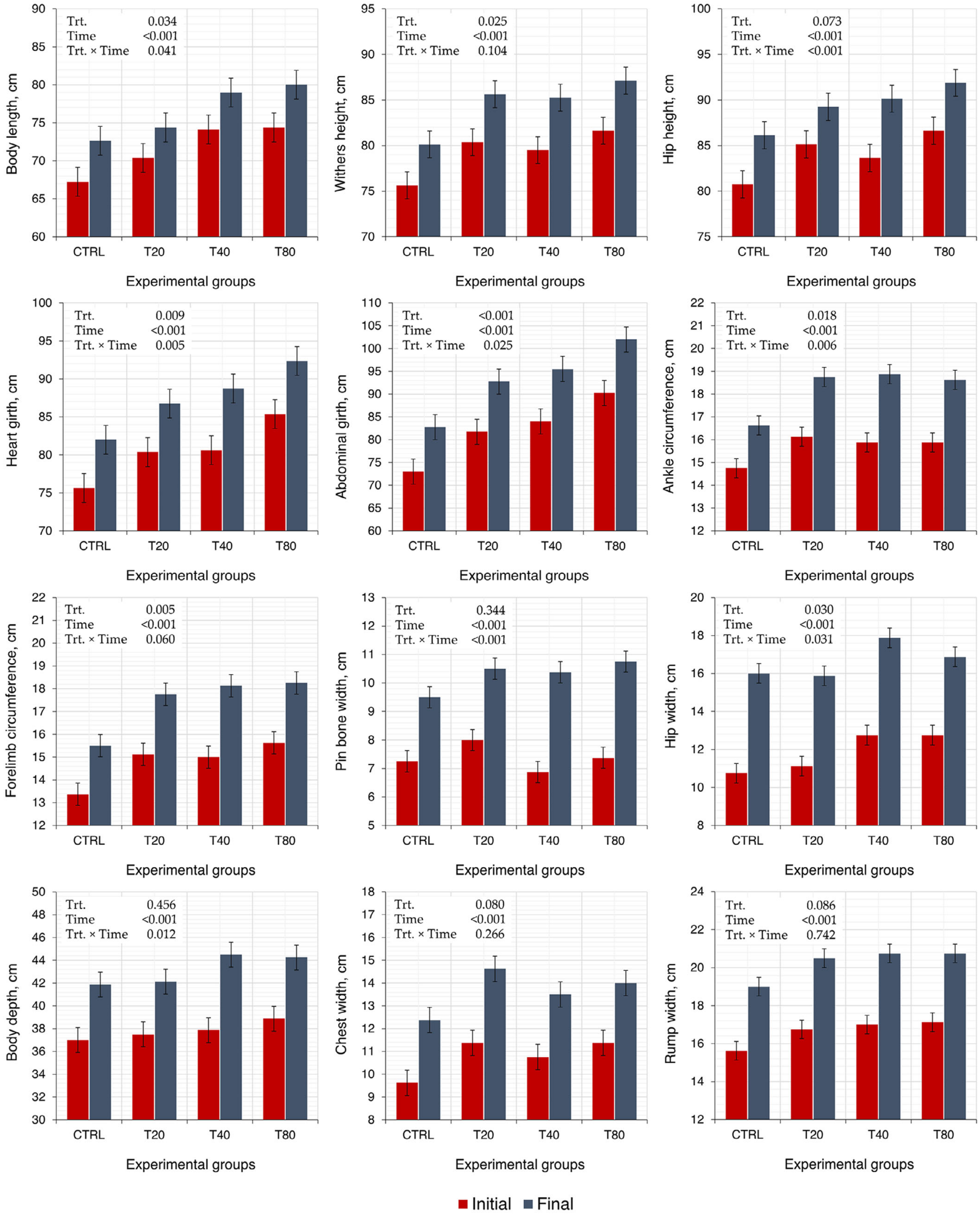

FIGURE 2 | Effects of increasing levels of dietary CNM on the skeletal growth indices of suckling calves under heat stress conditions ($n = 8$). CTRL, T20, T40 and T80 represent supplementation of CNM at 0, 20, 40 and 80 mg/day/animal, respectively; Trt. and Trt. × Time represent p-values for the effect of treatments and treatment × Time interaction, respectively.

TABLE 3 | Effects of different levels of dietary CNM on the nutrient digestibility of suckling calves under heat stress condition (n = 8).

Digestibility	Treatments*				SEM[1]	*p*-value[2]		
	CTRL	T20	T40	T80		ANOVA	L	Q
Dry matter, %	59.08	50.71	57.82	53.07	3.789	0.429	0.548	0.655
Organic matter, %	61.97	53.24	60.98	56.00	3.987	0.432	0.595	0.660
Ether extract, %	66.16	65.09	68.35	64.68	4.837	0.961	0.961	0.812
Crude protein, %	80.72	79.41	82.08	78.35	3.884	0.920	0.808	0.767
Neutral detergent fibre, %	44.50[a]	33.94[ab]	22.33[b]	37.63[ab]	3.939	0.021	0.115	0.010

*CTRL, T20, T40 and T80 represents supplementation of CNM at 0, 20, 40 and 80 mg/day/animal, respectively; [1] standard error of the means; [2] ANOVA, analysis of variance, where L and Q, represents *p*-values for linear and quadratic models tested via polynomial contrast method.

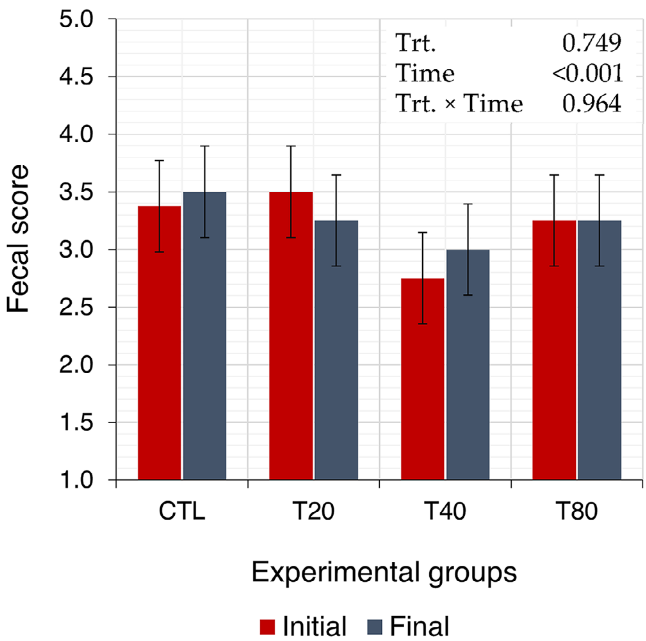

FIGURE 3 | Effects of increasing levels of dietary CNM on faecal score of suckling calves under heat stress conditions (n = 8). CTRL, T20, T40 and T80 represent supplementation of CNM at 0, 20, 40 and 80 mg/day/animal, respectively; Trt. and Trt. × Time represents p-values for the effect of treatments and treatment × Time interaction, respectively.

bone width showed no significant effect from dietary levels of CNM (p = 0.344); however, it was significantly influenced by the interaction between treatment and time (p < 0.001). Hip width was significantly influenced by CNM supplementation (p = 0.030), with a significant treatment × time interaction (p = 0.031). Similarly, a significant treatment × time interaction was detected for body depth (p = 0.012), though CNM supplementation itself did not have a significant effect (p = 0.456). Finally, while there was a tendency for CNM supplementation to affect chest width (p = 0.080) and rump width (p = 0.086), neither showed a significant treatment × time interaction (p = 0.266 and p = 0.742, respectively).

3.5 | Faecal Consistency

Figure 3 illustrates the impact of increasing dietary CNM levels on the faecal consistency score of suckling calves under heat stress conditions. Neither the dietary CNM levels (p = 0.749) nor their interaction with time (p = 0.964) had a significant effect on the faecal consistency score in these conditions.

4 | Discussion

The current study explored the potential of dietary CNM supplementation to mitigate the adverse effects of heat stress on growth performance, nutrient digestibility and skeletal development in suckling Simmental calves. Heat stress is known to impair metabolic function, reduce feed intake, and negatively affect digestion, ultimately compromising growth and productivity in livestock. The use of natural additives to enhance animal performance, health and welfare is gaining increasing attention, particularly in the face of climate change. Among these, plant-based extracts such as curcumin—which can be produced even under suboptimal agricultural conditions—represent a promising strategy for supporting livestock farming in high-risk environments (Felini et al. 2024). Given curcumin's well-documented antioxidative, anti-inflammatory, and gut-modulatory properties, this study hypothesised that its nano-micelle formulation would improve bioavailability and exert beneficial effects under thermal stress.

4.1 | Climatic Conditions

The trial was conducted under persistent heat stress, characterised by high THI values. Previous research has indicated that prolonged exposure to heat stress disrupts homeostasis, elevating oxidative stress and inflammatory markers while impairing metabolic efficiency (Bokharaeian et al. 2025a). Heat-stressed ruminants experience increased energy demands for thermoregulation, often leading to a trade-off between maintenance and productive functions. Consequently, evaluating CNM supplementation within this context provides insights into its efficacy as a nutritional intervention for mitigating heat-induced physiological stress.

4.2 | Growth Performance

The observed improvement in ADG and total weight gain with CNM supplementation under heat stress conditions suggests its potential role in mitigating growth suppression commonly associated with thermal stress. The enhanced growth response, particularly at 40 mg/day/animal, aligns with previous findings demonstrating curcumin's ability to support ruminant growth performance (Bokharaeian et al. 2024b; Marcon et al. 2021). This effect may be attributed to curcumin's well-documented antioxidant and anti-inflammatory properties, which help alleviate oxidative damage and systemic inflammation induced by heat stress (Bokharaeian et al. 2025a), thereby maintaining cellular function and metabolic efficiency. Additionally, curcumin has been reported to modulate the hypothalamic-pituitary-adrenal (HPA) axis, reducing stress-induced cortisol secretion, which in turn preserves anabolic processes crucial for growth (Xu et al. 2006). The significant increase in DMI with CNM supplementation further supports this notion, as improved feed intake under stress conditions is often linked to enhanced gut health and immune modulation. Curcumin's role in maintaining intestinal integrity and promoting beneficial microbial populations may contribute to this effect, as previously reported in studies on heat-stressed livestock (Abdel-Moneim et al. 2024). However, the absence of a significant effect on FCR suggests that while CNM improved nutrient intake and weight gain, it may not have directly enhanced feed conversion efficiency. This contrasts with studies in other species that have reported improved FCR with curcumin supplementation (Bokharaeian et al. 2024a), highlighting the species-specific and environmental influences on curcumin's efficacy. It is possible that CNM's benefits on feed efficiency are more pronounced under prolonged supplementation or different stress intensities, as curcumin's bioavailability and metabolic fate can vary depending on physiological conditions and dietary composition. Further investigations into the precise metabolic pathways involved in CNM's action under heat stress are warranted to fully elucidate its long-term benefits for ruminant productivity.

4.3 | Nutrient Digestibility

The dose-dependent response of NDF digestibility to CNM supplementation suggests an optimal effect at intermediate levels, which aligns with previous studies highlighting curcumin's role in modulating rumen microbial activity (Bokharaeian et al. 2024b; Tian et al. 2023). The increased NDF digestibility at 40 mg CNM may stem from curcumin's anti-inflammatory and antioxidant properties, which enhance the abundance and activity of fibrolytic microbes responsible for fibre degradation (Zhu and He 2024). This mechanism supports findings by Bokharaeian et al. (2024b), where a similar CNM dose improved fibre digestibility in fattening lambs.

However, the lack of significant effects on DM, OM, CP and EE digestibility warrants critical reflection. These nutrients undergo complex digestive processes involving enzymatic digestion, microbial fermentation, and absorption along the gastrointestinal tract. It is possible that CNM exerted only localised or subtle effects insufficient to measurably alter total tract digestibility. Moreover, curcumin's impact may have been more pronounced on microbial-mediated fibre degradation than on enzymatic protein or fat digestion (Xie et al. 2024). Similar findings by Vorlaphim et al. (2011) suggest that while moderate curcumin supplementation can enhance fibre digestion, higher doses may interfere with microbial homeostasis, leading to reduced ADF digestibility.

4.4 | Skeletal Growth Indices

The enhanced skeletal growth observed in CNM-supplemented calves is likely a result of improved nutrient utilisation and metabolic efficiency, leading to greater daily feed intake and, consequently, increased skeletal dimensions. Energy balance regulation plays a crucial role in this process, ensuring metabolic flexibility and optimising nutrient absorption for growth (Ganson et al. 2022). Curcumin has been shown to enhance gut health by modulating the intestinal microbiota and improving nutrient absorption, which may contribute to better growth performance in young ruminants (Tian et al. 2023). Additionally, genetic predisposition influences appetite control and fat accumulation, affecting overall body expansion (Davis et al. 2022). The observed increases in body length, withers height, chest girth, abdominal girth, ankle circumference, wrist circumference, and chest width suggest an overall expansion in body capacity, reflecting differences in nutrient intake efficiency and daily weight gain. Metabolic adaptation enhances energy storage efficiency and adjusts resting metabolism, further contributing to skeletal growth. A well-balanced crude protein-to-metabolisable energy ratio is critical in early-life development, as it supports skeletal growth by providing essential amino acids and energy substrates for bone and muscle development (Khan et al. 2016). Additionally, early-life protein intake has been linked to enhanced intestinal metabolic rates, which facilitate the absorption of key minerals such as calcium and phosphorus, essential for proper skeletal ossification (Kazemi-Bonchenari et al. 2018). Skeletal development is also influenced by maternal nutrition during gestation, as in utero nutrient availability affects muscle fibre formation and subsequent calf growth potential (Marquez et al. 2017). Hormonal and digestive factors, such as increased stomach size due to overeating, further impact hunger and satiation responses, reinforcing long-term body expansion (Davis et al. 2022). The role of curcumin in modulating oxidative stress and inflammation further supports skeletal integrity under heat stress conditions, as chronic heat exposure is known to impair mineral homeostasis and reduce bone formation (Chevalier et al. 2020). Evolutionarily, fat storage mechanisms provided survival advantages, but in modern environments, they contribute to excessive weight gain. These findings align with previous reports demonstrating that bioactive compounds with antioxidant and anti-inflammatory properties can mitigate the negative impacts of environmental stressors on skeletal growth and overall performance in young ruminants (McGrath et al. 2018). Collectively, these factors indicate that skeletal growth is not merely a consequence of increased nutrient intake but rather a result of intricate biological adaptations shaping nutrient utilisation and metabolic efficiency.

4.5 | Faecal Consistency

Faecal consistency serves as a crucial indicator of gastrointestinal health and nutrient utilisation efficiency in young ruminants, as it reflects the interaction between dietary composition, gut microbiota, and digestive function. The absence of significant differences in faecal consistency among CNM-supplemented calves suggests that curcumin's potential benefits on gut health may be influenced by environmental stressors such as heat stress, dehydration, and shifts in microbial populations, which could override its expected modulatory effects. Early calfhood faecal characteristics are largely governed by environmental, sanitary, and managerial conditions rather than solely by dietary interventions (Rajabpour et al. 2024). Previous studies have demonstrated that curcumin supplementation can modulate gut health and faecal consistency under various conditions (Alıc Ural et al. 2024), but its effects appear to be dose- and environment-dependent. Glombowsky et al. (2020) reported that dietary curcumin did not alter faecal scoring in calves, corroborating the present findings. Additionally, Lesmeister et al. (2004) highlighted that during early calfhood, when starter feed intake is minimal, faecal characteristics are less influenced by diet composition and more by external factors. The faecal consistency scores in this study remained within the normal physiological range for growing calves (Probo and Veronesi 2022), indicating that CNM supplementation did not induce digestive disturbances nor significantly enhance gut stability under heat stress conditions. While curcumin has been noted for its anti-inflammatory and gut-protective properties, its efficacy under heat stress conditions warrants further investigation to determine optimal dosages and potential synergistic effects with other gut-modulating additives.

5 | Conclusions

In conclusion, dietary CNM supplementation demonstrated significant potential in mitigating the adverse effects of heat stress on suckling Simmental calves by improving growth performance and skeletal development. The 40 mg/day dose showed the most consistent benefits, likely due to CNM's antioxidant, anti-inflammatory, and gut-modulatory properties. Additionally, the improvement in NDF digestibility at intermediate CNM levels highlights its role in optimising fibre utilisation, which is crucial for sustaining growth under challenging environmental conditions. Practically, CNM may offer a natural, scalable nutritional strategy for improving resilience in calves raised under hot conditions. However, the lack of significant effects on faecal consistency and other nutrient digestibility parameters highlights the complexity of CNM's effects and the need for further research. Limitations of the present study included the relatively short trial duration and the lack of mechanistic insights into the observed responses. Therefore, future research should focus on long-term effects, precise metabolic pathways, and optimal dosage strategies to maximise its benefits across different ruminant production systems. These efforts will help translate current findings into more precise, effective applications in livestock nutrition and heat stress management.

Author Contributions

Conceptualisation: Mehdi PiyadehKouhsar, Taghi Ghoorchi, Abdolhakim Toghdory, Mostafa HosseinAbadi and Mostafa Bokharaeian. Data curation: Mehdi PiyadehKouhsar, Taghi Ghoorchi and Mostafa Bokharaeian. Formal analysis: Mehdi PiyadehKouhsar and Mostafa Bokharaeian. Funding acquisition: Mehdi PiyadehKouhsar and Taghi Ghoorchi. Investigation: Mehdi PiyadehKouhsar, Taghi Ghoorchi, Abdolhakim Toghdory and Mostafa HosseinAbadi. Methodology: Mehdi PiyadehKouhsar, Taghi Ghoorchi, Abdolhakim Toghdory and Mostafa Bokharaeian. Project administration: Mehdi PiyadehKouhsar and Taghi Ghoorchi. Resources: Mehdi PiyadehKouhsar. Software: Mehdi PiyadehKouhsar and Mostafa Bokharaeian. Supervision: Taghi Ghoorchi. Validation: Taghi Ghoorchi and Abdolhakim Toghdory. Visualisation: Mehdi PiyadehKouhsar and Mostafa Bokharaeian. Writing–original draft: Mehdi PiyadehKouhsar. Writing–review and editing: Mehdi PiyadehKouhsar and Mostafa Bokharaeian.

Ethics Statement

All experimental procedures involving animals were conducted in compliance with the International Guidelines for research involving animals (Directive 2010/63/EU) and were approved by the Animal Welfare and Ethics Committee of Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Peer Review

The peer review history for this article is available at https://publons.com/publon/10.1002/vms3.70454.

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