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Blood biochemical, mineral, and electrolyte responses of cattle to indigenous forage-based and locally formulated concentrate rations in Southern Ethiopia

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Abstract

This study evaluated the effects of indigenous forage-based diets supplemented with locally formulated concentrate rations on serum biochemical, enzymatic, mineral, and electrolyte profiles of cattle managed under pastoral and mixed crop-livestock systems in Southern Ethiopia. The experiment was conducted in Nyangatom (pastoral) and Salamago (mixed farming) districts using thirty clinically healthy indigenous cattle assigned to five dietary treatments: free grazing only (control) and four increasing levels of supplementation in a 2 × 5 factorial arrangement. Blood samples were collected before and after a 21-day feeding period and analyzed for key serum metabolites, liver enzymes, minerals, and electrolytes using standard laboratory procedures. Dietary supplementation significantly improved serum total protein, globulin, glucose, cholesterol, and urea concentrations, with higher responses observed at moderate to high supplementation levels ($P < 0.05$). Activities of hepatic enzymes (AST, ALT, and ALP) increased with dietary treatment, indicating enhanced metabolic activity without pathological deviation. Serum calcium, sodium, and potassium concentrations increased significantly with supplementation, while magnesium and phosphorus were primarily influenced by location. Treatment × location interactions were generally non-significant, suggesting consistent physiological responses across production systems. Correlation analyses revealed strong positive associations among protein, energy, lipid, and liver metabolism indicators, highlighting the integrated nature of metabolic adaptation to improved nutrition. Overall, the findings demonstrate that indigenous forage-based diets complemented with locally available concentrate resources effectively enhance metabolic and mineral status of cattle. This approach offers a sustainable, context-specific feeding strategy to improve cattle health and productivity in pastoral and agro-pastoral systems of Southern Ethiopia.

1. Introduction

Livestock production plays a central role in the livelihoods, food security, and socio-cultural systems of rural communities in Ethiopia, particularly in pastoral and agro-pastoral areas (FAO, 2023). Cattle contribute substantially to household income, draft power, milk production, and risk buffering, yet overall productivity remains low due to chronic feed shortages, poor feed quality, and seasonal variability in forage availability (Yisehak et al., 2020; Gizaw et al., 2024).

In arid and semi-arid regions such as the Lower Omo Valley, livestock production depends largely on natural rangelands dominated by indigenous grasses, shrubs, and browse species. These feed resources are often inadequate in crude protein and metabolizable energy during the dry season, leading to negative energy balance and impaired physiological performance (Alemayehu et al., 2021). Previous studies have demonstrated that strategic supplementation using protein- and energy-rich feeds can improve animal performance and health, but the use of locally available indigenous forages and concentrate resources remains insufficiently documented under pastoral conditions (Bekele et al., 2022).

Blood biochemical and mineral parameters are widely recognized as sensitive indicators of nutritional status, metabolic efficiency, and health of livestock (Deribe et al., 2020). Changes in serum metabolites such as glucose, total protein, urea, cholesterol, and liver enzymes reflect dietary adequacy, rumen fermentation efficiency, and hepatic function (Mekuriaw et al., 2021). Likewise, serum mineral and electrolyte profiles provide insight into mineral balance, homeostasis, and adaptation to environmental stressors (Zewdie et al., 2022).

Nyangatom and Salamago districts represent contrasting livestock production systems within South Omo Zone, where pastoral and mixed crop–livestock practices coexist under varying agro-ecological conditions. Despite the abundance of indigenous forage species and local concentrate ingredients, limited empirical evidence exists on their combined effects on cattle metabolic responses across these systems. Therefore, this study aimed to evaluate the effects of indigenous forage-based and locally formulated concentrate rations on serum biochemical, enzymatic, mineral, and electrolyte profiles of cattle in pastoral and mixed farming systems of Southern Ethiopia, and to compare responses across agro-ecological contexts.

2. Materials and Methods

2.1 The Study Area

The study was conducted in two distinct districts of the South Omo Zone, Southern Ethiopia: Nyangatom (pastoral system) and Salamago (mixed crop–livestock system).

Nyangatom District is located in the arid to semi-arid lowland plains of the Lower Omo Valley, with an altitude ranging from approximately 350 to 700 m above sea level. The climate is characterized by high mean annual temperatures (often exceeding 30°C, reaching up to 38°C) and low, erratic bimodal rainfall averaging 350–600 mm annually. Frequent droughts and prolonged dry periods shape a predominantly transhumant pastoral livelihood system (CSA, 2021). The sparse population relies on livestock (cattle, goats, and sheep), with seasonal mobility dictated by pasture and water availability. Feed resources are primarily from natural rangelands of indigenous grasses, browse species, and shrubs.

Salamago District occupies lowland to mid-altitude zone (approximately 800–1,800 m above sea level) with a milder climate. Mean annual temperatures range from 20–28°C, and annual rainfall is higher (700–1,200 mm) with a unimodal to weak bimodal pattern. These conditions support a mixed crop–livestock farming system (Yisehak et al., 2020). The district has a higher population density, with livelihoods combining crop cultivation (e.g., maize, sorghum) and livestock rearing. Feed resources include natural pasture, crop residues, and limited local concentrates, with indigenous forage remaining crucial during dry seasons.

2.2. Experimental Animals and Design

Thirty clinically healthy indigenous cattle (15 from each district) of similar age, sex, breed, and initial body weight were selected, following matching procedures recommended for tropical nutrition studies (Deribe et al., 2020). Animals were individually tagged and randomly assigned to one of five dietary treatments in a completely randomized design with a 2 × 5 factorial arrangement (location × diet), with six animals per treatment group.

2.3. Dietary Treatments and Formulation

Five dietary treatments were evaluated:

T1

Free grazing only (control)

T2

Low level of supplementary ration (e.g., 0.5% of body weight)

T3

Moderate level of supplementary ration (e.g., 1.0% of body weight)

T4

High level of supplementary ration (e.g., 1.5% of body weight)

T5

Very high level of supplementary ration (e.g., 2.0% of body weight)

Note

The exact inclusion levels (e.g., % body weight, dry matter intake, or specific nutrient density) were specified based on the experimental design.

2.4. Feeding Protocol

Animals were individually fed for 28 days. The supplementary ration was offered once daily in the morning, followed by free grazing. Clean drinking water was available ad libitum. Daily feed intake was recorded throughout the experimental period.

2.5. Blood Sample Collection and Processing

Blood samples were collected from the jugular vein before the trial (day 0) and after 21 days of feeding, following standard veterinary procedures (Deribe et al., 2020). Samples were drawn into vacutainer tubes containing acid citrate dextrose as anticoagulant, at a consistent morning hour to minimize diurnal variation (Zewdie et al., 2022). Serum was separated by centrifugation at 4,000 rpm for 5 min and stored at − 20°C until analysis.

2.6. Biochemical and Mineral Analysis

Serum biochemical parameters were analyzed using standard spectrophotometric methods described previously (Mekuriaw et al., 2021): **Metabolites**: total protein, albumin, globulin, glucose, creatinine, urea, total bilirubin, triglycerides, cholesterol, as well as **Enzymes**: aspartate aminotransferase (AST), alanine aminotransferase (ALT), alkaline phosphatase (ALP). Minerals (calcium, magnesium, phosphorus) and electrolytes (sodium, potassium, chloride) were measured using atomic absorption spectrometry and ion-selective electrodes, respectively. Analyses were performed at Sodo Animal Health Laboratory.

2.7. Statistical Analysis

Data were checked for normality and homogeneity of variance. A two-way analysis of variance (ANOVA) was used to evaluate the effects of location, dietary treatment, and their interaction, consistent with analytical approaches in similar nutrition studies. Mean separation was performed using Tukey's HSD test at $P < 0.05$. Pearson's correlation coefficients were calculated to evaluate relationships among serum parameters. All analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Serum biochemical metabolites and enzyme activities

The results of Table 1 below indicated that Dietary treatment levels significantly influenced several serum biochemical parameters of cattle in both Nyangatom (NY) and Salamago (SL) districts. Total protein (TP) concentrations increased progressively with increasing dietary treatment levels, with the highest values recorded in T4 and T5, particularly in Nyangatom cattle ($P < 0.01$). Albumin (Alb) concentrations were significantly affected by location ($P < 0.05$), with generally higher values observed in Salamago compared with Nyangatom, while treatment effects were not significant.

Globulin (Glb) levels showed a significant response to dietary treatment ($P < 0.01$), with higher concentrations observed at intermediate to higher inclusion levels (T3–T5) in both locations. Serum glucose concentrations were significantly affected by treatment ($P < 0.01$), with higher values recorded in T3 -T5 compared with T1 and T2, particularly in Salamago cattle.

Creatinine concentrations increased with dietary treatment level in Nyangatom cattle ($P < 0.01$), whereas no consistent trend was observed in Salamago. Activities of hepatic enzymes, including aspartate aminotransferase (AST), alanine aminotransferase (ALT), and alkaline phosphatase (ALP), were significantly influenced by dietary treatments ($P < 0.05$), with higher activities generally observed at higher treatment levels. Cholesterol concentrations increased progressively with dietary treatment level in both districts ($P < 0.05$).

Serum urea and total bilirubin concentrations showed moderate increases with increasing dietary treatment levels; however, treatment × location interactions were not significant for most biochemical parameters, indicating similar response patterns across districts.

Table 1
Effects of dietary treatment inclusion levels on serum metabolites and enzymatic profiles of cattle in Nyangatom and Salamago districts

Parameters	L	Treatment, Mean						*P value*		
		T1	**T2**	**T3**	**T4**	**T5**	**SEM**	**L**	**T**	**L×T**
TP	NY	5.79 ^{c}	6.4 ^{b2}	6.7 ^{ab2}	6.97 ^{a2}	6.98 ^{a}	0.9	0.011	0.004	0.774
	SL	6.38 ^{b}	7.17 ^{a1}	7.32 ^{a1}	7.30 ^{a1}	7.07 ^{ab}				
Alb	NY	3.18	3.15	3.2	3.2	3.58	0.58	0.01	0.397	0.563
	SL	3.7	3.72	3.72	3.78	3.37				
Glb	NY	2.78 ^{b}	3.25 ^{ab}	3.12 ^{ab}	3.77 ^{a}	3.37 ^{ab}	0.07	0.507	0.004	0.563
	SL	2.68 ^{b}	3.45 ^{a}	3.60 ^{a}	3.52 ^{a}	3.52 ^{a}				
Glucose, *mg/dl*	NY	56.83 ^{ab}	47.67 ^{b}	65.83 ^{a}	70 ^{a}	66.67 ^{a}	1.68	0.26	0.001	0.990
	SL	65.00 ^{ab}	56.83 ^{b}	75.83 ^{a}	76.33 ^{a}	71.67 ^{a}				
Creatin, *g/dl*	NY	0.83^{2}	0.84^{2}	0.97^{2}	1.03^{2}	1.09	0.04	0.000	0.403	0.085
	SL	1.49^{1}	1.09^{1}	1.23^{1}	1.34^{1}	1.07				
AST, *g/dl*	NY	36.83 ^{b2}	53.33 ^{a2}	50.67 ^{a2}	61 ^{a2}	56.5 ^{a2}	1.72	0.001	0.021	0.376
	SL	71.67 ^{ab1}	76.00 ^{ab1}	64.33 ^{b1}	82.17 ^{a1}	74 ^{ab1}				
Cholesterol	NY	51.67 ^{c2}	57.83 ^{bc2}	68.67 ^{bc2}	85.33 ^{ab}	91 ^{a2}	3.08	0.002	0.014	0.350
	SL	73.17 ^{b1}	97.83 ^{a1}	93 ^{ab1}	85.33 ^{ab}	104.67 ^{a1}				
Urea, *mg/dl*	NY	27 ^{b}	31.5 ^{ab}	33.83 ^{ab}	37 ^{a}	37 ^{a}	0.94	.417	0.40	0.913
	SL	29.83	35.17	36.17	37.17	35.67				
Total Bilirubin, *g/dl*	NY	1.55 ^{b}	2.11 ^{ab}	4.14 ^{a}	2.53 ^{ab}	2.64 ^{ab}	0.18	0.336	0.035	0.568
	SL	2.79	2.35	3.48	3.01	3.05				
Triglycerides	NY	26.18	35.94	38.41	39.98	35.49	1.35	0.598	0.096	0.547
	SL	31.22	44.31	37.41	34.81	35.41				
ALT	NY	21.77 ^{b}	33.87 ^{ab}	40.6 ^{ab}	49.03 ^{a}	45.47 ^{a}	1.67	0.025	0.001	0.385
	SL	23.27	22.20	39.63	32.27	34.90				
ALP	NY	54.17 ^{b2}	85.67 ^{ab}	118.96 ^{a2}	108.7 ^{ab2}	134.83 ^{a2}	4.09	0.01	0.001	0.351
	SL	90.33 ^{b1}	75.17 ^{b}	153.8 ^{a1}	126.3 ^{ab1}	165.83^{a1}				

TP: Total Protein; Alb: Albumin; Glb: Globulin; Creatin: Creatinine; AST: Aspartate Aminotransferase; ALT: Alanine Aminotransferase; ALP: Alkaline Phosphatase; SEM: Standard Error of the Mean; L: Location (NY: Nyangatom, SL: Salamago);

T: Treatment; L×T: Interaction between Location and Treatment; P values correspond to the main effects of Location (L) and Treatment (T), and their interaction (L×T).

3.2. Serum mineral and electrolyte profiles

The research findings in Table 2 below shown that dietary treatments significantly influenced serum mineral and electrolyte concentrations of cattle in both Nyangatom and Salamago districts. Serum calcium concentrations increased progressively with increasing dietary treatment levels ($P < 0.01$), with the highest values observed in cattle receiving T4 and T5 diets in both locations. This pattern indicates a consistent response of calcium status to dietary treatment, regardless of production system. Magnesium concentrations, however, were primarily influenced by location ($P < 0.01$), with higher mean values recorded in Nyangatom cattle compared with those from Salamago.

Serum phosphorus concentrations differed significantly between locations ($P < 0.01$) but were not affected by dietary treatment level. Sodium and potassium concentrations responded significantly to dietary treatments ($P < 0.01$), with potassium showing a marked increase at higher treatment levels, particularly in Salamago cattle. Chloride concentrations were also significantly affected by dietary treatment ($P < 0.01$) and exhibited a declining trend as dietary inclusion levels increased. Treatment × location interactions were not significant for most mineral and electrolyte parameters, suggesting comparable response patterns across districts.

Table 2
Effects of dietary treatments on serum mineral and electrolyte profiles of cattle in Nyangatom and Salamago districts

Parameters	L	Treatment, Mean						*P value*		
		T1	**T2**	**T3**	**T4**	**T5**	**SEM**	**L**	**T**	**L×T**
Calcium	NY	7.04	7.35	8.03	9.50	8.18	0.16	0.01	0.000	0.815
	SL	6.29 ^{b}	5.77 ^{b}	7.52 ^{ab}	8.57 ^{a}	7.68 ^{ab}				
Magnesium	NY	3.54	3.62	3.48	4.08	3.38	0.09	0.006	0.076	0.860
	SL	2.88	3.43	3.03	3.50	2.58				
Phosphorus	NY	4.68	4.90	4.78	4.88	4.43	0.079	0.003	0.389	0.832
	SL	3.96	4.28	4.57	4.30	4.12				
Sodium	NY	132.8	149.5	144.3	136.2	135.00	0.86	0.107	0.001	0.793
	SL	128.0	146.5 ^{a}	139.7 ^{ab}	133.2	136.33				
Potassium	NY	3.52	5.55	5.63	6.83	4.91	0.14	0.563	0.001	0.444
	SL	3.39 ^{b}	5.27 ^{a}	5.02 ^{ab}	6.17 ^{a}	5.78 ^{a}				
Chloride	NY	104.3	98.8	109.8	101.5	87.83	1.73	0.288	0.002	0.953
	SL	104.5 ^{ab}	96.3 ^{ab}	106.7 ^{a}	93.00 ^{ab}	83.17 ^{b}				

L: Location (NY: Nyangatom, SL: Salamago); T: Treatment; L×T: Interaction between Location and Treatment; SEM: Standard Error of the Mean. P values correspond to the main effects of Location (L) and Treatment (T), and their interaction (L×T).

3.3. Correlation among serum biochemical parameters

Pearson's correlation analysis of serum biochemical parameters in Salamago cattle is presented in Table 3. Total protein (TP) showed significant positive correlations with globulin ($r = 0.845$, $P < 0.05$), glucose ($r = 0.576$, $P < 0.01$), cholesterol ($r = 0.542$, $P < 0.01$), urea ($r = 0.738$, $P < 0.01$), and total bilirubin ($r = 0.572$, $P < 0.01$). TP also exhibited weaker, non-significant correlations with creatinine, AST, triglycerides, ALT, and ALP.

Albumin had limited associations, showing a significant positive correlation only with total bilirubin (r = 0.421, P < 0.05), whereas correlations with other metabolites and enzymes were generally weak or non-significant. Globulin was positively correlated with glucose (r = 0.616, P < 0.01), cholesterol (r = 0.588, P < 0.01), urea (r = 0.674, P < 0.01), and total bilirubin (r = 0.421, P < 0.05).

Glucose was positively correlated with urea (r = 0.494, P < 0.01), total bilirubin (r = 0.492, P < 0.01), ALT (r = 0.534, P < 0.01), and cholesterol (r = 0.382, P < 0.05). Creatinine showed a significant correlation with total bilirubin (r = 0.401, P < 0.05) only, while AST was positively correlated with cholesterol (r = 0.461, P < 0.05). Cholesterol was significantly associated with urea (r = 0.493, P < 0.01) and ALT (r = 0.392, P < 0.05). Urea was positively correlated with total bilirubin (r = 0.431, P < 0.05). Other parameters, including triglycerides, ALT, and ALP, showed limited and non-significant associations.

Table 3
Pearson's correlation coefficient among serum biochemical parameters of Salamago cattle

	Alb	Glb	Glu	Creatin	AST	Chol.	Urea	Total B.	Trigly.	ALT	ALP
TP	0.456*	0.845*	0.576**	0.74	0.277	0.542**	0.738**	0.572**	0.294	0.274	0.224
Alb		-0.43	.105	0.130	0.12	0.044	0.269	0.421*	0.046	-0.029	-0.254
Glb			0.616**	0.036	0.358	0.588**	0.674**	0.421*	0.334	0.243	0.39
Glu				0.384*	0.339	0.382*	0.494**	0.492**	0.218	0.534**	0.392*
Creatin					-0.049	-0.145	0.092	0.401*	-0.144	0.1	0,012
AST						0.461*	0.313	-0.076	0.089	0.096	-0.119
Chol.							0.493**	0.311	0.392*	0.309	0.218
Urea								0.431*	0.223	0.296	0.242
Total B.									0.273	0.235	0.247
Trigly.										0.205	-0.084
ALT											0.182

3.4 Correlation among serum biochemical parameters in Nyangatom cattle

Pearson's correlation coefficients among serum biochemical parameters of Nyangatom cattle are presented in Table 4 below. Total protein (TP) showed significant positive correlations with most serum metabolites and enzymes, including glucose (r = 0.82, p < 0.01), AST (r = 0.80, p < 0.01), cholesterol (r = 0.85, p < 0.01), urea (r = 0.85, p < 0.01), and total bilirubin (r = 0.63, p < 0.01). TP was also moderately correlated with albumin, globulin, triglycerides, ALT, and ALP (p < 0.05–0.01).

Albumin was significantly correlated with glucose (r = 0.61, p < 0.01), AST (r = 0.41, p < 0.05), cholesterol (r = 0.44, p < 0.05), urea (r = 0.54, p < 0.01), and total bilirubin (r = 0.59, p < 0.01), whereas its correlations with creatinine, triglycerides, ALT, and ALP were not significant. Globulin showed significant positive correlations with glucose, creatinine, AST, cholesterol, urea, ALT, and ALP (p < 0.05–0.01). Glucose was strongly correlated with cholesterol (r = 0.85, p < 0.01), urea (r = 0.71, p < 0.01), total bilirubin (r = 0.64, p < 0.01), creatinine (r = 0.59, p < 0.01), and AST (r = 0.54, p < 0.01), and moderately correlated with ALT and ALP (p < 0.05–0.01). Creatinine showed significant associations with AST, cholesterol, urea, total bilirubin, and ALT (p < 0.05–0.01), but not with triglycerides or ALP. AST was positively correlated with cholesterol (r = 0.65, p < 0.01), urea (r = 0.83, p < 0.01), total bilirubin (r = 0.53, p < 0.01), triglycerides (r = 0.63, p < 0.05), and ALT (r = 0.49, p < 0.01). Cholesterol exhibited significant correlations with urea, total bilirubin, triglycerides, ALT, and ALP (p < 0.05–0.01). Urea was moderately correlated with total bilirubin, triglycerides, ALT, and ALP (p < 0.05–0.01). Total bilirubin showed significant correlations with triglycerides

and ALT ($p < 0.05–0.01$), while triglycerides were not significantly correlated with ALT or ALP. A strong positive correlation was observed between ALT and ALP ($r = 0.65$, $p < 0.01$).

Table 4
Pearson's correlation coefficient among serum biochemical parameters of Nyangatom cattle

	Alb	Glb	Glu	Creatin	AST	Chol.	Urea	Total B.	Trigly.	ALT	ALP
TP	0.62**	0.67*	0.82**	0.6**	0.80**	0.85**	0.85**	0.63**	0.66**	0.60**	0.47**
Alb		0.04	0.61**	0.21	0.41*	0.44*	0.54**	0.59**	0.28	0.31	0.21
Glb			0.48**	0.38*	0.58**	0.62**	0.48**	0.23	0.49*	0.39*	0.29
Glu				0.59**	0.54**	0.85**	0.71**	0.64**	0.49*	0.59**	0.45*
Creatin					0.51**	0.53**	0.66**	0.39*	0.54*	0.34	0.26
AST						0.65**	0.83**	0.53**	0.63*	0.49**	0.34
Chol.							0.72**	0.51*	0.58**	0.59**	0.59**
Urea								0.51*	0.48**	0.49**	0.47**
Total B.									0.55**	0.42*	0.32
Trigly.										0.27	0.14
ALT											0.65**

3.5. Correlation among serum mineral and electrolyte profiles of Salamago cattle

The results in Table 5 described below indicated that Pearson's correlation analysis among serum mineral and electrolyte parameters of Salamago cattle revealed mostly weak to moderate associations. Potassium showed a significant positive correlation with sodium ($r = 0.485$, $P < 0.01$), indicating coordinated variation between these two electrolytes. Magnesium was positively correlated with sodium ($r = 0.399$, $P < 0.05$) and chloride ($r = 0.459$, $P < 0.05$).

Calcium showed weak, non-significant correlations with all measured electrolytes and minerals, including magnesium, phosphorus, sodium, potassium, and chloride. Phosphorus was weakly correlated with sodium and potassium and showed a negative, non-significant association with chloride. Potassium exhibited a negative but non-significant correlation with chloride.

Table 5
Pearson's correlation *coefficient* among mineral and electrolyte profiles of Salamago cattle

	Magnesium	Phosphorus	Sodium	Potassium	Chloride
Calcium	0.082	0.284	-0.224	0.246	-0.265
Magnesium		0.293	0.399*	0.279	0.459*
Phosphorus			0.185	0.273	-0.198
Sodium				0.485**	0.172
Potassium					-0.340

3.6. Correlation among serum mineral and electrolyte profiles of Nyangatom cattle

In Nyangatom cattle, Pearson's correlation analysis demonstrated several moderate associations among serum mineral and electrolyte parameters shown in Table 6 below. Calcium was positively correlated with magnesium ($r = 0.499$, $P < 0.01$), while its associations with phosphorus, sodium, potassium, and chloride were weak and non-significant. Magnesium showed a significant positive correlation with potassium ($r = 0.415$, $P < 0.05$).

Sodium exhibited a moderate positive correlation with potassium ($r = 0.392$, $P < 0.05$) and a weak positive association with chloride. Phosphorus showed weak, non-significant correlations with sodium, potassium, and chloride. Potassium was weakly and non-significantly correlated with chloride.

Table 6
Pearson's correlation *coefficient* among mineral and electrolyte profiles of Nyangatom cattle

	Magnesium	Phosphorus	Sodium	Potassium	chloride
Calcium	0.499**	0.115	-0.070	0.328	-0.1
Magnesium		0.257	-0.061	0.415*	0.114
Phosphorus			0.203	0.264	-0.080
Sodium				0.392*	0.329
Potassium					0.093

4. Discussion

4.1: Effects of dietary treatments on serum metabolites and enzymatic profiles

The results indicate significant effects of dietary treatment levels and location on serum biochemical parameters in cattle from Nyangatom (NY) and Salamago (SL) districts. Total protein (TP) showed higher levels in SL across all treatments, which may reflect better nutritional status or metabolic adaptation in this region, consistent with findings that regional forage quality directly influences protein synthesis in grazing ruminants (Kaneko et al., 2008; Alemayehu et al., 2021). The increase in TP with treatment level suggests improved protein metabolism with dietary supplementation, aligning with recent studies on strategic feed supplementation in tropical cattle systems (Dereje et al., 2023).

Glucose levels were generally higher in SL and increased with treatment level, particularly in T4 and T5, indicating enhanced energy availability, possibly due to improved gluconeogenesis or carbohydrate intake (Humann-Ziehank et al., 2022). AST and ALT, markers of hepatic function, were elevated in SL, which may be attributed to higher metabolic demand, dietary composition, or even subclinical responses to environmental stressors common in certain agro-ecological zones (Mekonnen et al., 2021). ALT showed a significant treatment effect in NY, suggesting that dietary interventions may influence liver enzyme activity more prominently in certain regions, highlighting the importance of location-specific nutritional management (Gelaye et al., 2023).

Cholesterol levels increased with treatment in both districts, reflecting improved lipid metabolism and energy status, though values were consistently higher in SL, a pattern also observed in cattle with access to diverse browse species (Tekle et al., 2022). Urea levels remained stable across treatments, indicating consistent nitrogen metabolism and efficient urea recycling, which is often maintained under varying protein intakes in adapted indigenous breeds (Asmare, 2020). ALP, associated with bone and liver metabolism, showed marked increases with treatment, especially in SL, which may indicate enhanced metabolic or growth activity, as ALP is a recognized biomarker for bone turnover and hepatic function in growing cattle (Payne & Payne, 1987; Worku et al., 2024).

Overall, the dietary treatments positively influenced several metabolic parameters, with location-specific responses underscoring the critical interaction between nutrition, environment, and genotype in cattle physiology.

4.2. Effects of dietary treatments on serum mineral and electrolyte profiles

Dietary treatments significantly affected serum mineral and electrolyte profiles, with notable differences between districts. Calcium levels were higher in NY, particularly in T4, which may reflect better calcium absorption or supplementation efficacy, potentially linked to differences in soil pH, forage calcium content, or vitamin D status, as highlighted in recent studies on mineral bioavailability in tropical forages (McDowell, 2003; Solomon et al., 2022). Magnesium and phosphorus levels were generally stable, though phosphorus was lower in SL, possibly due to inherent soil mineral deficiencies or antagonistic interactions with other minerals in the local forages, a common challenge in extensive grazing systems (Mousa & Alhidary, 2023).

Sodium and potassium showed significant treatment effects, with T2 and T3 resulting in higher sodium levels in both districts. This aligns with findings that supplemental mineral mixes can effectively correct transient electrolyte imbalances in cattle (Shenkoru et al., 2021). Potassium increased with treatment in NY, especially in T4, which may support better electrolyte balance, muscle function, and rumen buffering capacity (Khalid et al., 2022). Chloride levels decreased with higher treatment levels in both districts, which could indicate altered acid-base balance or renal adaptation to maintain homeostasis, a physiological response documented in cattle under dietary electrolyte manipulation (Bayissa et al., 2023).

These findings suggest that while dietary supplementation can enhance mineral status, regional differences in soil geochemistry, water quality, and forage composition remain dominant factors that must be integrated into nutritional planning for sustainable cattle production (Desta & Beyene, 2024).

4.3. Pearson’s correlation among serum biochemical parameters in Salamago cattle

The correlation analysis for Salamago cattle revealed a network of significant relationships among serum biochemical parameters, reflecting interconnected metabolic and physiological pathways. Total protein (TP) exhibited strong positive correlations with globulin (Glb) and moderate associations with glucose, cholesterol, urea, and total bilirubin. This pattern suggests that protein metabolism is closely linked to energy homeostasis, lipid metabolism, and nitrogen excretion in this population, a finding consistent with systems biology approaches that reveal co-regulation of these pathways under nutritional modulation (Gebreyohannes et al., 2022).

Glucose demonstrated significant positive correlations with creatinine, cholesterol, urea, total bilirubin, ALT, and ALP. These associations indicate that glucose metabolism is not only central to energy provision but also interrelated with renal function (creatinine), lipid regulation, and hepatic activity, supporting the concept of a tightly regulated "metabolic engine" in ruminants (Huang et al., 2021). The strong correlation between glucose and ALT ($r = 0.534$) may reflect enhanced gluconeogenic activity or liver involvement in glucose regulation, as ALT is increasingly recognized for its role beyond mere liver damage, including in gluconeogenesis (Tadesse & Reta, 2023).

AST showed a notable positive correlation with cholesterol ($r = 0.461$), supporting the established role of liver enzymes in lipid metabolism and export (Kraft & Dürr, 2005). Cholesterol itself was positively associated with urea and triglycerides, suggesting coordinated lipid and protein metabolic pathways, possibly mediated by insulin and other regulatory hormones (Mekuriaw et al., 2024). Urea was further correlated with total bilirubin, which may point to shared regulatory mechanisms in nitrogen metabolism and liver function, particularly in the context of the urea cycle and heme catabolism (Yokus & Cakir, 2006).

Overall, the correlation matrix underscores a tightly coupled metabolic system in Salamago cattle, where dietary or physiological changes affecting one parameter may have cascading effects on others, emphasizing the need for a holistic

view in nutritional interventions.

4.4. Pearson's correlation among serum biochemical parameters in Nyangatom cattle

In Nyangatom cattle, the correlation analysis revealed a highly integrated metabolic network, with particularly strong associations among protein, energy, and lipid metabolism indicators. Total protein (TP) was significantly correlated with nearly all parameters, especially glucose, cholesterol, urea, and liver enzymes, highlighting its central role as a marker of overall metabolic and nutritional status, a pattern often seen in well-nourished and metabolically active herds (Ayele et al., 2023).

Glucose showed robust positive correlations with cholesterol, urea, total bilirubin, and liver enzymes (ALT and ALP), reinforcing its pivotal role as the primary energy currency and its interaction with hepatic and renal functions. The exceptionally strong link between glucose and cholesterol ($r = 0.85$) suggests a coordinated regulation of energy and lipid metabolism in this group, possibly driven by insulin sensitivity and lipogenic pathways that are highly active in certain cattle ecotypes (Getachew et al., 2022).

Cholesterol was positively associated with urea, total bilirubin, triglycerides, ALT, and ALP. These relationships point to a close interplay between lipid metabolism, protein catabolism, and liver function, where the liver serves as the central hub orchestrating the synthesis, degradation, and interconversion of these metabolites (Piccione et al., 2012). The correlation between urea and total bilirubin further supports the interconnectedness of nitrogen metabolism and hepatobiliary function, reflecting shared metabolic fates of amino acids and heme (Sartin et al., 1985).

Additionally, the strong positive correlation between ALT and ALP ($r = 0.65$) indicates parallel activity of these liver enzymes, possibly reflecting adaptive or responsive hepatic mechanisms under dietary influence, and may be indicative of hepatocellular activity related to both protein turnover and bone metabolism (Woldehanna et al., 2024). These findings illustrate a coherent and responsive metabolic network in Nyangatom cattle, suggesting that dietary interventions can simultaneously influence multiple, interconnected physiological pathways.

4.5. Pearson's correlation among mineral and electrolyte profiles of Salamago cattle

The correlation analysis of mineral and electrolyte profiles in Salamago cattle indicates distinct physiological interactions, with a moderate number of significant associations. The strong positive correlation between sodium and potassium ($r = 0.485$, $p < 0.01$) highlights their well-documented synergistic role in maintaining osmotic balance, neuromuscular function, and acid-base homeostasis (Goff, 2018). Recent studies in grazing cattle have reinforced that sodium and potassium levels are closely co-regulated, especially under conditions of varied forage mineral content (Neves et al., 2021).

Notably, magnesium exhibited positive correlations with sodium ($r = 0.399$) and chloride ($r = 0.459$), which may reflect its involvement in electrolyte transport and cellular ion balance. Emerging research suggests that magnesium status can influence sodium retention and chloride distribution, particularly in ruminants fed region-specific diets (Menta et al., 2022). The absence of a strong calcium-phosphorus correlation, contrary to classical expectations, may indicate independent regulatory mechanisms or environmental influences such as soil mineral composition and forage type (Pegorer et al., 2023). Overall, these correlations suggest that mineral homeostasis in Salamago cattle is influenced by both physiological interactions and local nutritional factors.

4.6. Pearson's Correlation among Mineral and Electrolyte Profiles of Nyangatom Cattle

The inter-mineral relationships in Nyangatom cattle reveal a more integrated network than observed in Salamago, with several significant correlations underscoring key metabolic linkages. The strong positive correlation between calcium and magnesium ($r = 0.499$, $p < 0.01$) suggests co-regulation in absorption or excretion, possibly mediated by shared transport mechanisms or

dietary interactions. Recent studies indicate that calcium and magnesium homeostasis can be closely linked in ruminants, especially when dietary levels of one influence the metabolism of the other (Silva et al., 2023).

Additionally, the correlation between magnesium and potassium (r = 0.415) aligns with their combined roles in enzyme activation and membrane stability, which is consistent with findings in cattle under varied nutritional management (Menta et al., 2022). The sodium-potassium correlation (r = 0.392), though slightly weaker than in Salamago, remains physiologically significant and reflects their joint role in maintaining cellular function and fluid balance (Neves et al., 2021).

The absence of an inverse calcium-phosphorus correlation, similar to the findings in Salamago, may reflect adaptive mineral homeostasis in response to local forage mineral profiles or supplementation strategies. This pattern has been noted in recent research on pastoral cattle systems, where traditional grazing regimes can alter expected mineral ratios (Pegorer et al., 2023). Overall, the correlation structure in Nyangatom cattle points to a tightly regulated mineral metabolism shaped by both physiological demands and environmental context.

5. Conclusions

This study demonstrates that supplementing indigenous forage-based diets with locally formulated concentrate rations significantly enhances the metabolic and mineral status of cattle in pastoral and mixed farming systems of Southern Ethiopia. Key serum parameters - including total protein, glucose, cholesterol, and essential minerals such as calcium, sodium, and potassium - improved with increasing supplementation levels, reflecting better nutritional balance and physiological adaptation. The consistent responses across contrasting agro-ecological zones underscore the robustness and adaptability of locally available feed resources. These findings advocate for the integration of context-specific, low-cost supplementation strategies into livestock development programs. By leveraging indigenous forages and local concentrates, pastoral and agro-pastoral systems can improve cattle health, productivity, and resilience, offering a sustainable pathway toward enhanced food security and livelihood stability in Ethiopia and similar arid and semi-arid regions.

6. Future Lines of Research Work

Future research should explore long-term supplementation effects on reproduction, growth, and milk yield. Investigating the economic feasibility and adoption barriers of local feed formulations is essential. Studies assessing the climate resilience of indigenous forage species under varying drought intensities are needed. Evaluating breed-specific metabolic responses and mineral bioavailability from local feeds will refine nutritional strategies. Finally, integrating digital monitoring tools for real-time health and nutrient status could enhance precision feeding in pastoral systems. These efforts will support scalable, sustainable livestock nutrition solutions for Ethiopia and similar agro-pastoral regions.

Declarations

Ethics Approval and Consent to Participate

The experimental procedures followed national animal welfare guidelines and were approved by the institutional research ethics committee of Arba Minch University. Informed consent was obtained from participating pastoralists and farmers.

Consent for Publication

All authors have approved the manuscript and consent to its publication.

Availability of Data and Materials

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests.

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Authors' Contributions

Tesfaye Edjem Tkapel designed the experiment, collected data, and drafted the manuscript. Yisehak Kechero (Professor) supervised the study and contributed to data analysis and manuscript revision. Asrat Guja (Dr.) provided technical guidance and critical review. All authors read and approved the final manuscript.

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