Unlocking the Feed Potential: A Comparative Analysis of Indigenous Grasses, Legumes, Shrubs, and Trees for Sustainable Animal Nutrition in Ethiopia

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Research Article

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Abstract

This study provides a comprehensive nutritional evaluation of indigenous forage species across the lowland and midland agro-ecologies of Southern Ethiopia. A range of species, including grasses, legumes, shrubs, and fodder trees, were analyzed for key nutritional parameters: dry matter (DM), crude protein (CP), fiber fractions (NDF, ADF, and ADL), metabolizable energy (ME), and macro-minerals (K, Ca, and Mg). Data were subjected to analysis of variance (ANOVA) with post-hoc tests, revealing statistically significant variations ($P < 0.05$) across species and agro-ecologies. Midland species consistently exhibited superior nutritional quality, with significantly higher CP (e.g., up to 22.55% in *Melilotus albus*) and ME values (e.g., up to 2361.01 kcal/kg in *Moringa* species) compared to lowland varieties. Conversely, lowland forages had higher DM, ash content, and fiber fractions, indicating lower digestibility. Macro-mineral analysis showed significant inter-species differences, with *Colona floribunda* being notably rich in potassium (12.66 g/kg) and calcium (3.57 g/kg). The findings underscore the critical influence of agro-ecology on forage quality. This research provides robust, evidence-based data crucial for developing sustainable livestock feeding systems. By enabling the targeted use of high-quality indigenous forages, these results can help smallholder producers enhance animal productivity, optimize supplementation strategies, and reduce dependence on expensive commercial feeds.

1. Introduction

Ethiopia possesses one of the largest livestock populations in Africa, underscoring the sector's critical role in rural livelihoods and the national economy. Livestock contribute substantially to food security, household income, draft power, and socio-cultural functions for millions of smallholder farmers across diverse agro-ecological zones (Belete et al., 2024; Regasa & Masho, 2024). Despite this large livestock resource base, productivity remains far below its potential due to several constraints, among which feed scarcity and poor forage quality are among the most critical. Feed shortages are particularly severe during the dry season when natural pastures decline sharply in both biomass and nutritional value, and reliance on low-quality sources such as crop residues increases (Mengistu et al., 2021; Regasa & Masho, 2024).

In most Ethiopian smallholder mixed crop–livestock systems, animals depend largely on natural grazing lands, crop residues, and indigenous forage species as primary feed resources (Belete et al., 2024). However, these resources often fail to meet livestock nutritional requirements for optimal growth, reproduction, and production due to low crude protein (CP) contents and high structural fiber fractions (Mengistu et al., 2021; Belete et al., 2024; Regasa & Masho, 2024). Moreover, natural pastures and residues are characterized by fluctuating quality and availability that are insufficient to sustain productive animals year-round (Regasa & Masho, 2024; Shiferaw et al., 2025).

Indigenous forage resources-including grasses, legumes, shrubs, and fodder trees-form the backbone of ruminant feeding in many tropical settings and are generally well adapted to local climatic conditions and environmental stresses (Belete et al., 2024). Nevertheless, their nutritional potential remains underutilized due to limited localized scientific information on their chemical composition and feeding value. The nutritional quality of forages is primarily determined by parameters such as dry matter (DM), crude protein (CP), fiber fractions including neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and metabolizable energy (ME). These components influence digestibility, voluntary intake, and overall animal performance. In addition, macro-minerals like potassium (K), calcium (Ca), and magnesium (Mg) are essential for physiological functions such as bone formation, enzyme activity, and nerve transmission (Belete et al., 2024).

Agro-ecological factors such as rainfall, altitude, soil fertility, and temperature significantly influence plant growth and the nutritional composition of forage species. For example, forages grown in mid-altitude areas often contain higher protein and energy levels due to more favorable climatic conditions, whereas species in harsher lowland environments tend to accumulate higher fiber and DM contents as adaptations to stress (Belete et al., 2024). Understanding these agro-ecological variations in forage quality is essential for designing efficient livestock feeding strategies.

However, comprehensive comparative data on indigenous forage species across different agro-ecological zones of southern Ethiopia remain limited. Therefore, the present study was conducted to evaluate the nutritional composition of selected indigenous grasses, legumes, shrubs, and fodder trees across lowland and midland agro-ecologies. Specifically, the study aimed to compare the nutritional composition (DM, CP, NDF, ADF, ADL, and ME) of indigenous forage species across agro-ecologies, assess the macro-mineral content (K, Ca, and Mg) of selected forage species, identify nutritionally superior species suitable for livestock feeding systems, and provide evidence-based recommendations for improving forage utilization in smallholder livestock production systems.

Significance of the Study

The findings of this study are expected to generate vital data on the nutritional quality and mineral content of key indigenous forage species. Such information will be instrumental for farmers, extension agents, and policymakers in making informed decisions regarding forage selection, utilization, and supplementation strategies. Ultimately, this will contribute to improving livestock productivity, enhancing smallholder livelihoods, and promoting sustainable agricultural systems in Ethiopia.

2. Materials and Methods

2.1. Agro-Ecological Description of the Study Area

The study areas represent two distinct agro-ecological zones of southern Ethiopia: lowland and midland environments (Fig. 1a). The lowland districts (Dasenech, Nyangatom, and Salamago) in South Omo Zone are characterized by arid to semi-arid climatic conditions, with annual rainfall ranging from approximately 350 to 700 mm, irregular distribution, and frequent drought occurrences (FAO, 2012; Pierce et al., 2014). The mean annual temperature ranges between 25 and 35°C, reflecting the hot climate of the Rift Valley lowlands. The altitude varies from about 350 to 900 meters above sea level, and the dominant soils are sandy loam and alluvial soils with relatively low organic matter and moderate to low fertility, which influence vegetation composition and forage productivity (Grimshaw et al., 1995). In contrast, the midland agro-ecology, represented by Kolme District in Konso Zone, experiences relatively more favorable climatic conditions, with annual rainfall ranging from 800 to 1200 mm and a mean annual temperature of 18–25°C. The altitude ranges from approximately 1200 to 1800 meters above sea level, creating cooler and more humid conditions that support higher vegetation productivity. The predominant soils are loamy and clay-loam types with relatively better soil fertility, although soil degradation and seasonal moisture stress may still occur in some areas due to recurrent dry periods (FAO, 2012).

Forage sampling was conducted during the main growing (rainy) season, at the early flowering stage of the plants, which corresponds to the typical grazing period in both agro-ecological zones (Minson, 1990; Buxton & Fales, 1994). These variations in rainfall, temperature, altitude, soil type, and drought frequency create distinct ecological conditions that significantly influence plant growth patterns and the nutritional composition of indigenous forage species across the two agro-ecologies (Pierce et al., 2014; Grimshaw et al., 1995).

2.2 Feed Sampling and Nutrient Analysis

Forage samples were collected from the identified study districts within the lowland (Dasenech, Nyangatom, and Salamago) and midland (Kolme) agro-ecological zones. Sampling was conducted during the main growing (rainy) season, consistent with the period of active plant growth described in Section 2.1 (Minson, 1990). Representative indigenous forage species were selected based on their availability and importance in local grazing systems. Samples were harvested at the early flowering stage, widely recognized as the optimal stage for balancing biomass yield and nutritional quality, and reflecting the typical grazing period for livestock in both agro-ecologies (Buxton & Fales, 1994; Van Soest, 1994). At each sampling site, forage samples were collected using a systematic approach to ensure representativeness. Plant materials were clipped at a uniform height above ground level to simulate grazing conditions. Multiple subsamples were taken from different locations within each site and then composited to form a representative sample for laboratory analysis (AOAC, 2006). Forage samples were properly labeled and air-dried under shade immediately after collection to reduce moisture content and minimize nutrient loss prior to transport and laboratory analysis. Consequently, the reported dry matter (DM) values reflect pre-dried samples rather than the original moisture content of fresh forage (AOAC, 2006). Forage samples were air-dried under shade immediately after collection to reduce moisture content prior to laboratory analysis. Therefore, the reported dry matter (DM) values represent the dry matter of pre-dried samples and not the original fresh forage moisture content." Composite samples were air-dried under shade to prevent nutrient degradation, ground to pass through a 1 mm sieve using a Wiley mill, and stored in airtight containers until analysis. All results were expressed on a dry matter (DM) basis, and analyses were performed in triplicate, with mean values reported alongside the standard error of the mean (SEM).

The proximate composition, including dry matter (DM), ash, crude protein (CP), ether extract (EE), and crude fiber (CF), was determined following the standard procedures of the Association of Official Analytical Chemists (AOAC, 2023). Dry matter (DM) content was determined by oven-drying the samples at 105°C until a constant weight was obtained, while ash content was measured by incinerating the samples in a muffle furnace at 550°C for 4 hours. Crude protein (CP) was analyzed using the Kjeldahl method, where nitrogen content was determined and multiplied by 6.25 to estimate protein content. Ether extract (EE) was determined using Soxhlet extraction with petroleum ether as the solvent and crude fiber (CF) was measured through sequential acid and alkali digestion.

Structural carbohydrates were analyzed using the detergent fiber system (Van Soest et al., 1991), with neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) determined through sequential refluxing. Soluble carbohydrates (SC) and nitrogen-free extract (NFE) were calculated by difference as NFE (%) = 100 − (CP + EE + Ash + CF), representing the non-fibrous carbohydrate fraction (McDonald et al., 2010).

Metabolizable energy (ME, kcal/kg DM) was predicted from proximate composition using established feeding standards (Wiseman, 1987; NRC, 2001) or, when feasible, measured directly by bomb calorimetry and corrected for fecal, urinary, and gaseous energy losses. Quality control measures-including blanks, reference standards and instrument calibration-were strictly followed to ensure precision and reproducibility of results (AOAC, 2023; Yadav et al., 2023; USDA NRCS, 2023).

2.3 Statistical Analysis

All data were checked for normality and homogeneity of variances prior to analysis. The effects of agro-ecology and plant species on herbage biomass and nutritional composition were analyzed using a two-way analysis of variance (ANOVA) in a factorial arrangement. Agro-ecology and plant species were considered fixed effects, and their interaction effect was also included in the model. When significant differences were detected, pairwise comparisons among means were performed using Tukey's Honest Significant Difference (HSD) test. Means within the same column and agro-ecology with different superscript letters were considered significantly different at $P < 0.001$. All results are presented as mean ± SEM. Statistical analyses were conducted using the General Linear Model (GLM) procedure of SAS software (version 9.4). The statistical model used for the analysis was:

$$Y_{ijk} = \mu + A_i + Sj + (A*S)_{ij} + \varepsilon_{ijk}$$

Where Y_{ijk} = observation of the response variable (e.g., nutritional parameter) for the kth replication of the jth plant species in the ith agro-ecology; μ = overall mean; Ai = fixed effect of the ith agro-ecology (lowland or midland); S_j = fixed effect of the jth plant species; $(AS)_{ij}$ = interaction effect between the ith agro-ecology and the jth plant species; ε_{ijk} = random error term associated with the observation, assumed to be independently and normally distributed with mean zero and variance σ2

3. Result and Discussion

3.1. Nutritive Value of Grass Species across Lowland and Midland Agro-Ecologies

The chemical composition and metabolizable energy (ME) of grass species varied significantly between lowland and midland agro-ecologies in southern Ethiopia (Table 1). Dry matter (DM) content was consistently higher in lowland grasses (90–93%) than in midland grasses (83–89%). This difference is primarily attributed to the hotter and moisture-limited conditions in lowland environments, which accelerate plant dehydration and promote the accumulation of structural biomass. Under water stress, plants allocate more carbon to structural carbohydrates such as cellulose and lignin as an adaptive strategy to maintain cell integrity and reduce water loss. Similar climate-driven effects on forage dry matter accumulation have been reported in tropical grass systems (Tolera et al., 2021).

Ash content was also higher in lowland grasses (9.7–13.2%) compared to midland grasses (5.5–9.6%), suggesting variation in soil mineral composition and plant uptake efficiency across agro-ecologies (Wassie et al., 2018). In contrast, crude protein (CP) concentrations were markedly higher in midland grasses (8.2–17.6%) than in lowland grasses (4.2–10.3%). This can be mechanistically explained by more favorable growing conditions in midland areas, including moderate temperatures, improved soil moisture, and enhanced microbial activity, which collectively promote nitrogen mineralization and plant nitrogen uptake. Nitrogen availability is a key determinant of forage quality, directly influencing protein synthesis and overall nutritive value (Melo et al., 2025). Comparable trends have been observed in tropical forage systems where altitude and climate influence nutrient dynamics (Negassa et al., 2020).

Ether extract (EE), representing lipid fractions that contribute to dietary energy, was also higher in midland grasses (1.8–3.65%) than in lowland grasses (1.1–2.3%), further enhancing their energy value. In contrast, fiber fractions - including neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) - were generally higher in lowland grasses (NDF: 52–79%, ADF: 44–55%, ADL: 9.1–14.3%) than in midland grasses (NDF: 52–69%, ADF: 31–44%, ADL: 5.2–9.6%). Increased fiber and lignification are well-established plant responses to drought stress, enhancing structural rigidity but reducing digestibility. Elevated lignin content limits microbial degradation of cell walls in the rumen, thereby reducing voluntary intake and nutrient availability in ruminants (Van Soest, 1994; Jung &

Allen, 1995). Similar patterns have been reported in semi-arid rangelands, where increasing aridity leads to higher fiber content and lower forage quality (Arroyo et al., 2024).

Crude fiber (CF) showed relatively minor variation, ranging from 23–36% in lowland and 21–34% in midland grasses, largely reflecting species-specific traits. Soluble carbohydrates (SC) were generally higher in lowland grasses (56–69%) than in midland grasses (48–55%), possibly due to reduced growth rates under stress conditions, leading to the accumulation of non-structural carbohydrates.

Metabolizable energy values were consistently higher in midland grasses (766–1970 kcal/kg DM) compared to lowland grasses (340–1504 kcal/kg DM) (Table 2). This difference reflects the combined effects of higher protein and lipid contents and lower structural fiber fractions in midland forages, which enhance digestibility and energy availability. Similar findings have been reported in other sub-humid and mid-altitude environments, where favorable climatic conditions improve forage quality and animal performance (Mekonnen et al., 2023).

Table 1
Chemical composition (% DM) and metabolizable energy (kcal/kg) of commonly utilized grass species across lowland and midland agro-ecologies in Southern Ethiopia

Parameter	Grass species (Lowland agro-ecology), Mean + SEM								
	Pennisetum purpureum	*Sporobolus indicus*	*Eragrostis pilosa*	*Cenchrus ciliaris*	*Danthonia unispicata*	*Panicum spp*	*Hyparrhenia hirta*	*Cynodon dactylon*	P-value
DM	90.37 ± 0.55^{b}	90.74 ± 1.19^{b}	91.4 ± 0.83^{b}	93.66 ± 0.58^{a}	90.71 ± 1.06^{b}	90.31 ± 0.63^{b}	90.56 ± 0.93^{b}	91.70 ± 0.23^{c}	0.002
ASH	12.49 ± 0.63^{a}	10.12 ± 0.68^{cd}	11.36 ± 1.16^{b}	9.70 ± 0.47^{d}	13.24 ± 0.04^{a}	10.57 ± 0.03b^{cd}	12.60 ± 0.01^{a}	10.85 ± 0.03^{bc}	< 0.001
CP	10.25 ± 0.61^{b}	8.18 ± 0.60^{d}	7.95 ± 0.39^{d}	6.84 ± 1.01^{c}	6.47 ± 0.01^{b}	4.99 ± 0.12^{a}	4.79 ± 0.009^{c}	4.23 ± 0.61d	< 0.001
EE	1.80 ± 0.21^{b}	1.12 ± 0.04^{d}	1.20 ± 0.10^{d}	2.30 ± 0.16^{a}	1.91 ± 0.01^{b}	1.97 ± 0.02^{b}	1.08 ± 0.02^{d}	1.40 ± 0.005^{c}	< 0.001
NDF	79.29 ± 1.56^{a}	70.51 ± 1.67^{c}	75.32 ± 2.62^{b}	68.84 ± 1.05^{c}	55.85 ± 0.75^{d}	52.17 ± 0.53^{f}	53.02 ± 0.67^{ef}	54.76 ± 0.69d^{e}	< 0.001
ADF	44.77 ± 6.79^{b}	49.37 ± 0.90^{b}	48.71 ± 2.35^{b}	48.35 ± 1.12^{b}	47.10 ± 1.05^{b}	48.75 ± 1.53^{a}	49.39 ± 0.26^{b}	55.43 ± 0.03^{b}	0.0130
ADL	14.05 ± 0.72^{a}	10.49 ± 0.56^{cd}	9.12 ± 0.52^{e}	9.87 ± 0.34^{d}	9.87 ± 0.15^{d}	10.68 ± 0.08^{c}	12.37 ± 0.23^{b}	14.28 ± 0.08^{a}	< 0.001
CF	25.95 ± 0^{d}	34.54 ± 0.97^{b}	24.56 ± 0.77^{a}	28.96 ± 0.29^{c}	28.54 ± 0.93^{c}	23.93 ± 0.41^{e}	34.05 ± 0.78^{e}	36.22 ± 0.49^{b}	< 0.001
SC	62.99 ± 7.33^{b}	59.74 ± 3.9^{bc}	59.24 ± 3.09b^{c}	69.18 ± 3.59^{a}	61.56 ± 0.88b^{c}	60.02 ± 0.34b^{c}	61.66 ± 0.74b^{c}	56.20 ± 1.13^{c}	0.0160
NFE	42.18 ± 1.0^{bc}	40.2 ± 0.84^{cde}	37.63 ± 3.21^{e}	46.22 ± 0.82^{a}	38.82 ± 1.75^{cd}	43.57 ± 1.07^{a}	45.46 ± 1.50^{a}	41.15 ± 0.52^{bcd}	< 0.001
ME(Kcal/Kg)	1237 ± 14^{b}	564 ± 45^{e}	1316 ± 69^{b}	1111 ± 6^{c}	982 ± 81^{d}	1504 ± 36^{a}	536 ± 65^{e}	340 ± 110^{f}	< 0.001
Grass species (Midland agro-ecology), Mean ± SEM									
DM	89.17 ± 1.17^{a}	85.12 ± 0.35^{c}	87.43 ± 0.57^{b}	83.6 ± 0.4^{d}	89.09 ± 0.57^{a}	83.31 ± 0.63^{d}	87.56 ± 0.93^{b}	87.7 ± 0.23^{b}	< 0.001
ASH	9.63 ± 0.18^{a}	6.45 ± 0.02^{e}	7.14 ± 0.02^{d}	5.54 ± 0.04^{g}	8.74 ± 0.04^{b}	6.07 ± 0.03^{f}	8.10 ± 0.01^{c}	6.35 ± 0.03^{e}	< 0.001
CP	17.6 ± 0.16^{c}	15.72 ± 0.12^{f}	8.39 ± 0.06^{e}	11.58 ± 0.16^{c}	8.18 ± 0.01^{e}	14.75 ± 0.12^{a}	12.34 ± 0.01^{b}	9.73 ± 0.61^{d}	< 0.001
EE	2.48 ± 0.07^{c}	1.77 ± 0.02^{g}	1.86 ± 0.06^{f}	3.65 ± 0.02^{a}	1.91 ± 0.01^{f}	3.17 ± 0.02^{b}	2.28 ± 0.02^{d}	2.6 ± 0.005^{b}	< 0.001
NDF	69.34 ± 1.54^{a}	57.31 ± 0.98^{cd}	65.3 ± 1.24^{b}	58.28 ± 1.03^{c}	55.85 ± 0.75d^{e}	52.17 ± 0.53^{g}	53.02 ± 0.67^{g}	54.76 ± 0.69^{f}	< 0.001
ADF	31.83 ± 0.82^{e}	41.01 ± 0.38^{b}	35.82 ± 0.27^{d}	37.51 ± 0.42^{c}	36.10 ± 1.05^{d}	44.43 ± 1.53^{a}	38.39 ± 0.26^{c}	37.75 ± 0.03^{c}	< 0.001
ADL	6.62 ± 0.21^{c}	5.55 ± 0.04^{e}	5.75 ± 0.04d^{e}	5.17 ± 0.15^{b}	7.66 ± 0.15^{f}	5.98 ± 0.09^{d}	7.67 ± 0.23^{b}	9.58 ± 0.08^{a}	< 0.001

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test), SEM, standard error of means

Parameter	Grass species (Lowland agro-ecology), Mean + SEM								
	Pennisetum purpureum	*Sporobolus indicus*	*Eragrostis pilosa*	*Cenchrus ciliaris*	*Danthonia unispicata*	*Panicum spp*	*Hyparrhenia hirta*	*Cynodon dactylon*	P-value
CF	23.5 ± 0.00^{d}	32.09 ± 0.97^{b}	33.77 ± 0.77^{a}	26.51 ± 0.29^{c}	26.09 ± 0.93^{c}	21.48 ± 0.41^{d}	22.11 ± 0.78^{d}	31.6 ± 0.49^{b}	< 0.001
SC	52.78 ± 0.1^{bc}	51.96 ± 1.09^{c}	48.83 ± 0.87^{d}	52.71 ± 0.48^{bc}	55.06 ± 0.88^{a}	53.52 ± 0.34^{b}	55.16 ± 0.74^{a}	49.70 ± 1.13^{d}	< 0.001
NFE	27.95 ± 1.36^{c}	37.07 ± 1.25^{b}	36.26 ± 0.76^{b}	36.31 ± 0.47^{b}	44.15 ± 1.28^{a}	36.82 ± 1.07^{b}	42.71 ± 1.5^{a}	37.4 ± 0.52^{b}	< 0.001
ME(Kcal/Kg)	1609 ± 10.15^{c}	1783 ± 69^{b}	766 ± 65^{f}	1572 ± 28^{c}	1383 ± 82^{d}	1970 ± 36^{a}	938 ± 84^{e}	1031 ± 45^{e}	< 0.001

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test), SEM, standard error of means

Overall, the observed differences in forage nutritive value between agro-ecologies are driven by interactions among climatic factors, soil fertility, and plant physiological responses. Lowland environments favor structural adaptation and stress tolerance at the expense of nutritional quality, whereas midland conditions promote nutrient-rich, more digestible forages. These findings align with global evidence highlighting the critical role of environmental gradients in shaping forage quality and have important implications for site-specific feed resource management strategies.

Table 2
Comparative summary of grass species between lowland and midland agro-ecologies

Parameter	Lowland	Midland	Trend / Interpretation
DM (%)	90–93	83–89	Lowland higher → drier grasses
Ash (%)	9.7–13.2	5.5–9.6	Lowland higher → more minerals
CP (%)	4.2–10.3	8.2–17.6	Midland higher → more protein
EE (%)	1.1–2.3	1.8–3.65	Midland higher → more energy-dense fats
NDF (%)	52–79	52–69	Lowland higher → more fibrous, less digestible
ADF (%)	44–55	31–44	Lowland higher → more structural fiber
ADL (%)	9.1–14.3	5.2–9.6	Lowland higher → higher lignin, lower digestibility
CF (%)	23–36	21–34	Variable; some lowland species higher
SC (%)	56–69	48–55	Lowland generally higher → more soluble carbohydrates
NFE (%)	37–46	28–44	Mixed; some lowland higher, but midland protein-rich species also strong
ME (Kcal/kg)	340–1504	766–1970	Midland higher → more metabolizable energy

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test), SEM, standard error of means

3.2 Nutritive value of legume species across lowland and midland agro-ecologies

The chemical composition of legume species varied significantly between lowland and midland agro-ecologies (Table 3), reflecting the strong influence of environmental conditions on plant physiological processes and nutrient accumulation. Dry matter (DM) content was consistently higher in lowland legumes (89.07–91.77%) than in midland legumes (80.35–86.77%), primarily due to higher temperatures

and lower moisture availability that accelerate plant dehydration and concentrate structural components (Alemayehu, 2021). Similarly, ash content was greater in lowland species (13.88–16.61%) compared to midland species (9.38–12.11%), suggesting enhanced mineral concentration under moisture stress conditions, where reduced biomass leads to nutrient accumulation (Tessema & Baars, 2019).

In contrast, crude protein (CP) concentrations were significantly higher in midland legumes (17.81–22.55%) than in lowland legumes (12.31–17.05%). This difference can be mechanistically attributed to enhanced biological nitrogen fixation (BNF) under favorable midland conditions, including optimal soil moisture, moderate temperatures, and improved soil fertility. Legumes form symbiotic associations with rhizobia, enabling atmospheric nitrogen fixation, which directly contributes to protein synthesis. Recent studies indicate that legumes can derive up to 70–75% of their nitrogen requirements from BNF, thereby substantially improving tissue nitrogen content and forage quality (Hu et al., 2023; Lepetit et al. 2023). Moreover, global assessments suggest that forage legumes can contribute up to 0.10–0.30 t N ha^{-1} $year^{-1}$ and reduce dependence on synthetic fertilizers by 35–45%, highlighting their broader agro-ecological importance. The higher CP levels in midland environments are therefore likely driven by increased rhizobial activity, improved nodulation efficiency, and enhanced nitrogen assimilation processes, all of which are highly sensitive to soil moisture and temperature regimes. Consistent with this, Negassa et al. (2020) reported that altitude-related improvements in soil conditions enhance nitrogen uptake and protein accumulation in legumes. Species such as *Melilotus albus* and *Amphicarpaea bracteata* exhibited particularly high CP values, indicating their suitability as strategic protein supplements in ruminant feeding systems. Ether extract (EE) content was also higher in midland legumes (3.89–4.44%) than in lowland legumes (2.69–3.24%), suggesting greater energy density, likely associated with enhanced metabolic activity and synthesis of cellular constituents under favorable growth conditions (Tolera et al., 2021). Consequently, metabolizable energy (ME) values were higher in midland legumes (1742–2085 kcal/kg DM) compared to lowland legumes (1276–1618 kcal/kg DM). This is consistent with their higher protein content and lower structural fiber fractions, both of which contribute to improved digestibility and energy availability. Similar trends have been reported globally, where legumes grown under optimal environmental conditions exhibit superior digestibility and feeding value compared to those grown under stress conditions. Fiber fractions showed contrasting patterns between agro-ecologies. While neutral detergent fiber (NDF) values were relatively similar (38.43–48.17%), acid detergent fiber (ADF) and acid detergent lignin (ADL) were markedly higher in lowland legumes (ADF: 32.81–40.87%; ADL: 8.64–11.14%) than in midland legumes (ADF: 21.81–29.87%; ADL: 3.94–6.44%). This can be explained by stress-induced lignification, a physiological adaptation to drought and heat stress. Under such conditions, plants increase lignin deposition to strengthen cell walls and reduce water loss; however, this reduces cell wall degradability and limits nutrient availability to rumen microbes (Van Soest et al., 2019). Increased lignification is widely recognized as a major constraint to forage quality in tropical and semi-arid production systems.

Lowland legumes also exhibited higher soluble carbohydrate contents (45.39–54.74%), which may reflect osmotic adjustment mechanisms that enable plants to cope with water stress by accumulating soluble sugars. However, this increase in non-structural carbohydrates does not compensate for the negative effects of elevated lignin on overall digestibility.

Beyond their nutritional value, legumes play a critical role in improving soil fertility and sustainability of agricultural systems. Their capacity for nitrogen fixation enhances soil nitrogen availability, supports subsequent crop production, and contributes to climate-smart agriculture. Globally, forage legumes such as lablab (*Lablab purpureus*) and sunnhemp (*Crotalaria juncea*) are recognized for their high crude protein yields and their role in integrated crop–livestock systems, reinforcing the relevance of the present findings beyond the study area.

Table 3
Chemical composition (%) and metabolizable energy (kcal/kg DM) of legume plants in lowland and midland agro-ecologies of Southern Ethiopia

Parameter	Woody layers including Legume Types (Lowland), Mean ± SEM				
	Melilotus albus	*Dotted dunbaria*	*Commelina benghalensis*	*Amphicarpaea bracteata*	P-value
DM	91.05 ± 0.22^{a}	91.77 ± 0.049^{a}	89.07 ± 0.81^{b}	89.35 ± 0.41^{b}	< 0.001
ASH	13.88 ± 0.04^{a}	16.61 ± 0.17^{d}	15.52 ± 0.02^{c}	14 ± 0.06^{b}	< 0.001
CP	17.05 ± 0.08^{a}	13.09 ± 0.05^{c}	12.31 ± 0.26^{d}	16.33 ± 0.16^{b}	< 0.001
EE	3.21 ± 0.10^{a}	3.24 ± 0.08^{a}	2.69 ± 0.03^{b}	3.11 ± 0.04^{a}	< 0.001
NDF	38.76 ± 0.27^{c}	38.43 ± 0.02^{c}	46.08 ± 0.99^{b}	48.17 ± 0.05^{a}	< 0.001
ADF	36.10 ± 0.55^{b}	33.63 ± 0.45^{c}	32.81 ± 0.72^{c}	40.87 ± 0.34^{a}	< 0.001
ADL	8.64 ± 0.05^{c}	8.78 ± 0.08^{b}	8.91 ± 0.11^{b}	11.14 ± 0.13^{a}	< 0.001
CF	24.48 ± 1.47^{a}	23.4 ± 0.23^{ab}	21.48 ± 1.03^{c}	21.77 ± 0.07^{bc}	0.012
SC	45.39 ± 1.71^{c}	53.13 ± 0.19^{ab}	54.74 ± 1.3^{a}	51.53 ± 0.18^{b}	< 0.001
NFE	30.41 ± 1.46^{c}	37.42 ± 0.27^{a}	37.06 ± 1.05^{a}	34.12 ± 0.21^{b}	< 0.001
ME(kcal/Kg)	1276 ± 126^{b}	1486 ± 14.79^{a}	1559 ± 91^{a}	1618 ± 3.41^{a}	0.002
Woody layer including Legume Types (Midland), Mean + SEM					
DM	86.77 ± 0.22^{a}	83.05 ± 0.05^{c}	84.07 ± 0.81^{b}	80.35 ± 0.41^{d}	< 0.001
ASH	9.38 ± 0.04^{a}	12.11 ± 0.17^{c}	11.02 ± 0.03^{b}	9.5 ± 0.06^{c}	< 0.001
CP	22.55 ± 0.09^{a}	18.59 ± 0.05^{c}	17.81 ± 0.26^{d}	21.83 ± 0.16^{b}	< 0.001
EE	4.41 ± 0.1^{a}	4.44 ± 0.07^{a}	3.89 ± 0.035^{b}	4.31 ± 0.035^{a}	< 0.001
NDF	38.76 ± 0.27^{c}	38.43 ± 0.01^{c}	46.08 ± 0.99^{b}	48.17 ± 0.05^{a}	< 0.001
ADF	25.10 ± 0.55^{b}	22.63 ± 0.46^{c}	21.81 ± 0.72^{c}	29.87 ± 0.33^{a}	< 0.001
ADL	3.94 ± 0.05^{c}	4.08 ± 0.07^{bc}	4.21 ± 0.11^{b}	6.44 ± 0.12^{a}	< 0.001
CF	22.03 ± 1.47^{a}	20.95 ± 0.24^{ab}	19.03 ± 1.03^{c}	19.32 ± 0.07^{bc}	0.011
SC	38.89 ± 1.71^{c}	46.63 ± 0.1^{ab}	48.24 ± 1.3^{a}	45.03 ± 0.18^{b}	< 0.001
NFE	25.66 ± 1.46^{c}	29.67 ± 0.27^{b}	32.31 ± 1.05^{a}	25.376 ± 0.21^{c}	< 0.001
ME(kcal/Kg)	1742 ± 126^{b}	1952 ± 15^{a}	2025 ± 91^{a}	2085 ± 3.41^{a}	0.003

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test), SEM, standard error of means

Overall (Table 3 and Table 4), the results demonstrate that while legumes inherently possess high protein potential due to their nitrogen-fixing ability, agro-ecological conditions strongly regulate the efficiency of nitrogen fixation, fiber accumulation, and overall nutritive value. Midland environments provide more favorable conditions for maximizing legume nutritional quality, particularly in terms of protein and metabolizable energy, whereas lowland conditions tend to promote structural fiber accumulation and reduced digestibility. These findings are consistent with broader global patterns and underscore the importance of agro-ecological targeting in forage development and livestock feeding strategies.

Table 4
Comparative summary of legume plants between lowland and midland agro-ecologies of Southern Ethiopia

Parameter	Lowland (Range)	Midland (Range)	Trend / Interpretation
DM (%)	89.07–91.77	80.35–86.77	Lowland higher → drier plants
Ash (%)	13.88–16.61	9.38–12.11	Lowland higher → more minerals
CP (%)	12.31–17.05	17.81–22.55	Midland higher → richer in protein
EE (%)	2.69–3.24	3.89–4.44	Midland higher → richer in fat
NDF (%)	38.43–48.17	38.43–48.17	Similar, slightly higher in lowland
ADF (%)	32.81–40.87	21.81–29.87	Lowland higher → more structural fiber
ADL (%)	8.64–11.14	3.94–6.44	Lowland higher → more lignin, less digestible
CF (%)	21.48–24.48	19.03–22.03	Lowland slightly higher
SC (%)	45.39–54.74	38.89–48.24	Lowland higher
NFE (%)	30.41–37.42	25.66–32.31	Midland slightly higher
ME (kcal/Kg)	1276–1618	1742–2085	Midland higher → more metabolizable energy

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at $P < 0.001$ (ANOVA, Tukey's HSD test), SEM, standard error of means

3.3 Nutritive value of shrub species across lowland and midland agro-ecologies

Shrub species exhibited considerable variation in chemical composition between lowland and midland agro-ecologies (Table 5), reflecting the influence of environmental conditions on plant structural development and nutrient dynamics. Dry matter (DM) content ranged from 87.15% to 96.55% in lowland shrubs and from 80.15% to 89.55% in midland shrubs, with consistently higher values in lowland environments. This pattern is primarily associated with drought adaptation, where reduced moisture availability accelerates tissue dehydration and concentrates structural components (Alemayehu et al., 2022). Similarly, ash content was higher in lowland shrubs (11.29–14.96%) than in midland shrubs (6.79–10.73%), suggesting mineral concentration effects under moisture stress and limited biomass production, a phenomenon commonly reported in browse and forage species growing under arid and semi-arid conditions (Khalil et al., 2021; Seleiman et al., 2021). In contrast, crude protein (CP) content was markedly greater in midland shrubs (9.31–22.17%) compared with lowland shrubs (3.81–14.14%). This difference can be mechanistically explained by improved soil moisture, enhanced nutrient availability, and more favorable temperature conditions in midland environments, which collectively promote nitrogen uptake, assimilation, and protein synthesis (Nigussie et al., 2023). Ether extract (EE) content followed a similar trend, with higher values in midland shrubs (1.91–5.49%) than in lowland shrubs (0.71–3.85%), indicating enhanced metabolic activity and greater accumulation of energy-rich compounds under favorable growing conditions. Fiber fractions, including neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL), were generally higher in lowland shrubs. ADL values, in particular, were substantially elevated in lowland species (10.24–13.22%) compared to midland species (5.12–8.52%). This reflects increased lignification as an adaptive response to drought and heat stress, where plants invest more in secondary cell wall formation to enhance structural rigidity and reduce water loss. However, this adaptation reduces cell wall degradability and limits nutrient availability to rumen microbes, thereby lowering forage quality (Van Soest, 2018; Castro-Montoya & Dickhoefer, 2020). Such stress-induced lignification is widely recognized as a key constraint to digestibility in tropical and semi-arid browse systems (Pereira-Crespo et al., 2026). In addition to structural components, shrub species often contain secondary metabolites such as tannins, which can further influence nutrient utilization. Tannins can bind proteins and carbohydrates, reducing their ruminal degradability, although moderate levels may improve nitrogen use efficiency and reduce methane emissions in ruminants (Aboagye et al. 2019). This highlights the dual nutritional and functional role of browse species in livestock feeding systems.

Metabolizable energy (ME) values ranged from 1062 to 1611 kcal/kg DM in lowland shrubs and from 1528 to 2130 kcal/kg DM in midland shrubs, with the highest value recorded for *Celtis ehrenbergiana* in the midland agro-ecology. The higher ME values in midland shrubs can be attributed to their lower fiber and lignin contents and higher nutrient density, which enhance digestibility and energy availability. Similar patterns have been reported globally, where browse species from sub-humid environments exhibit superior feeding value compared to those from arid zones.

Beyond their compositional differences, shrubs play a critical role in sustaining livestock production in tropical systems, particularly during dry seasons when herbaceous forages decline in both quantity and quality. A recent meta-analysis of Ethiopian browse species indicated that shrubs typically contain moderate to high CP levels (approximately 16–23%) and can significantly improve feed intake and digestibility when used as protein supplements (Belete et al., 2024), reinforcing their importance in mixed crop–livestock systems.

Table 5
Chemical composition (%) and metabolizable energy composition (kcal/Kg) of Shrub species in lowland and midland agro-ecologies of southern Ethiopia

Parameter	ShrubTypes (Lowland), Mean ± SEM						
	Celtis ehrenbergiana	*Fluegea virosa*	*Allowissadula holosericea*	*Buxus sinica var.parvifolia*	*Reseda luteola*	*Indigofera tinctoria*	P-value
DM	96.55 ± 0.03^{a}	92.4 ± 0.53^{b}	87.15 ± 0.5^{c}	88.7 ± 0.25^{c}	95.67 ± 0.18^{a}	90.22 ± 4.26^{bc}	< 0.001
ASH	11.85 ± 0.59^{b}	14.96 ± 0.035^{a}	11.29 ± 0.10^{b}	11.46 ± 0.08^{b}	11.35 ± 0.02^{b}	13.85 ± 2.11^{a}	< 0.001
CP	14.14± 4.69 1^{a}	11.32 ± 0.60^{ab}	11.99 ± 0.04^{ab}	8.85 ± 0.04^{c}	3.81 ± 0.09^{c}	9.51 ± 0.1 ^{b}	< 0.001
EE	1.75 ± 0.13^{c}	2.89 ± 0.10^{b}	3.85 ± 0.01^{a}	0.71 ± 0.01^{d}	2.45 ± 0.023^{bc}	3.69 ± 1.03^{a}	< 0.001
NDF	56.31 ± 1.01^{c}	59.56 ± 0.5^{b}	54.22 ± 1.22^{d}	63.14 ± 0.43^{a}	45.95 ± 0.08^{e}	44.11 ± 1.53^{f}	< 0.001
ADF	42.1 ± 1.02^{b}	42.27 ± 1.2^{b}	40.84 ± 0.93^{b}	54.38 ± 0.83^{a}	36.88 ± 0.50^{d}	38.91 ± 0.60^{c}	< 0.001
ADL	10.37 ± 0.22^{c}	11.37 ± 0.22^{b}	10.47 ± 0.04^{c}	13.22 ± 0.12^{a}	10.32 ± 0.43^{c}	10.24 ± 1.02^{c}	< 0.001
CF	22.01 ± 0.44^{c}	25.49 ± 1.18^{b}	29.74 ± 0.29^{a}	25.50 ± 0.70^{b}	26.20 ± 0.01^{b}	22.88 ± 2.9^{c}	0.011
SC	61.61 ± 1.28^{ab}	52.08 ± 1.93^{c}	49.87 ± 0.13^{c}	65.25± 0.87^{a}	57.77 ± 0.09^{b}	52.02 ± 5.22^{c}	< 0.001
NFE	51.41 ± 0.95^{a}	37.72± 0.70^{b}	30.27 ± 0.62^{c}	47.2 ± 0.61^{a}	46.8 ± 0.13^{a}	35.64 ± 9.22^{bc}	< 0.001
ME(kcal/Kg)	1611 ± 49^{a}	1557 ± 229^{a}	1237 ± 100^{bc}	1297 ± 1.2^{b}	1062 ± 25^{c}	1259 ± 65^{bc}	0.003
Shrub Types (Midland), Mean + SEM							
DM	89.55 ± 0.03^{a}	85.4 ± 0.53^{c}	80.15 ± 0.5^{d}	81.7 ± 0.25^{c}	88.46 ± 0.32^{b}	80.54 ± 0.46^{d}	< 0.001
ASH	7.35 ± 0.59^{b}	10.46 ± 0.035^{a}	6.79 ± 0.10^{c}	6.96 ± 0.08b^{c}	6.88 ± 0.04b^{c}	10.73 ± 0.32^{a}	< 0.001
CP	22.17 ± 0.34^{b}	17.49 ± 0.6^{a}	16.82 ± 0.04^{c}	15.02 ± 0.095^{d}	9.31 ± 0.075^{f}	14.30 ± 0.11^{e}	< 0.001
EE	2.95 ± 0.13^{e}	4.09 ± 0.10^{c}	5.05 ± 0.01^{b}	1.91 ± 0.01^{f}	3.66 ± 0.03^{d}	5.49 ± 0.01^{a}	< 0.001
NDF	56.31 ± 1.01^{c}	59.56 ± 0.5^{b}	54.22 ± 1.22^{d}	63.14 ± 0.43^{a}	45.85 ± 0.14^{e}	43.99 ± 1.34^{f}	< 0.001
ADF	31.1 ± 1.02^{b}	31.27 ± 1.2^{b}	29.84 ± 0.93^{b}	43.38 ± 0.83^{a}	26.45 ± 0.86^{c}	27.89 ± 0.64^{c}	< 0.001
ADL	5.67 ± 0.22^{cd}	6.67 ± 0.22^{b}	5.77 ± 0.05^{c}	8.52 ± 0.12^{a}	5.12 ± 0.76^{d}	6.08 ± 0.08b^{c}	< 0.001

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test), SEM, standard error of means

Parameter	ShrubTypes (Lowland), Mean ± SEM						
	Celtis ehrenbergiana	*Fluegea virosa*	*Allowissadula holosericea*	*Buxus sinica var.parvifolia*	*Reseda luteola*	*Indigofera tinctoria*	P-value
CF	19.56 ± 0.44^{c}	23.04 ± 1.18^{b}	27.29 ± 0.28^{a}	23.05 ± 0.70^{b}	23.76 ± 0.02^{b}	18.96 ± 0.4^{c}	< 0.011
SC	55.11 ± 1.28^{b}	45.58 ± 1.93^{d}	43.37 ± 0.13^{E}	58.75 ± 0.87^{a}	51.39 ± 0.17^{c}	42.64 ± 0.25^{e}	< 0.001
NFE	44.66 ± 0.95^{a}	30.97 ± 0.70^{c}	23.52 ± 0.62^{d}	40.45 ± 0.61^{b}	39.84 ± 0.31^{b}	23.17 ± 1.04^{d}	< 0.001
ME(kcal/Kg)	2130 ± 49^{a}	2077 ± 49^{a}	1762 ± 2^{b}	1726 ± 65^{b}	1528 ± 25^{c}	1703 ± 100^{b}	0.003

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test), SEM, standard error of means

Overall (Tables 5 and 6), the observed variation in shrub nutritive value is primarily driven by environmental stress, plant structural adaptation, and biochemical composition. Midland conditions favor higher protein and energy content due to improved growth conditions, whereas lowland environments promote lignification and mineral concentration, resulting in lower digestibility. These findings are consistent with broader global evidence and emphasize the importance of agro-ecological context in evaluating and utilizing browse resources for ruminant nutrition.

Table 6
Comparative summary of shrub species between lowland and midland agro-ecologies of southern Ethiopia

Parameter	Lowland (Range)	Midland (Range)	P-value	Trend / Interpretation
DM (%)	87.15–96.55	80.15–89.55	< 0.001	Lowland higher → drier plants
Ash (%)	11.29–14.96	6.79–10.73	< 0.001	Lowland higher → more minerals
CP (%)	3.81–14.14	9.31–22.17	< 0.001	Midland higher → richer in protein
EE (%)	0.71–3.85	1.91–5.49	< 0.001	Midland higher → richer in fat
NDF (%)	44.11–63.14	43.99–63.14	< 0.001	Similar range, midland slightly lower fiber
ADF (%)	36.88–54.38	26.45–43.38	< 0.001	Lowland higher → more structural fiber
ADL (%)	10.24–13.22	5.12–8.52	< 0.001	Lowland higher→ more lignin, less digestible
CF (%)	22.01–29.74	18.96–27.29	< 0.011	Lowland slightly higher
SC (%)	49.87–65.25	42.64–58.75	< 0.001	Lowland higher
NFE (%)	30.27–51.41	23.17–44.66	< 0.001	Midland higher
ME (kcal/Kg)	1062–1611	1528–2130	0.003	Midland higher → more metabolizable energy

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy, Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test).

3.4 Nutritional composition of fodder tree species across lowland and midland agro-ecologies

Fodder tree species exhibited significant variation in nutritional composition between lowland and midland agro-ecologies (Table 7), reflecting the influence of environmental conditions on plant physiology, nutrient allocation, and structural development. Dry matter (DM) content ranged from 88.01–93.33% in lowland trees and 77.99–89.87% in midland species, with consistently higher values in

lowland environments. This pattern is primarily associated with moisture stress, where reduced water availability accelerates tissue dehydration and concentrates structural components (Abebe et al., 2021). Similarly, ash content was higher in lowland trees (11.69–17.16%) than in midland species (5.54–12.77%), indicating mineral concentration effects under limited biomass production, a trend widely observed in woody species growing under arid conditions.

Crude protein (CP) concentrations were generally higher in midland tree species (5.77–24.20%) compared to lowland trees (6.30–16.34%), although some overlap occurred among species. This difference can be mechanistically explained by improved soil moisture, enhanced nutrient cycling, and more favorable temperature regimes in midland environments, which promote nitrogen uptake, assimilation, and protein synthesis. Tree foliage in tropical systems is widely recognized as a valuable protein source, often containing CP levels comparable to or exceeding those of conventional forages (Tadesse et al., 2024). *Moringa stenopetala* recorded the highest CP values in both agro-ecologies, confirming its importance as a high-quality protein supplement in livestock feeding systems (Tesfaye et al., 2023). Ether extract (EE) content was also higher in midland species (1.39–6.12%) than in lowland trees (1.86–4.11%), suggesting enhanced metabolic activity and greater accumulation of energy-rich compounds under favorable growing conditions. Consequently, metabolizable energy (ME) values ranged from 728–1834 kcal/kg DM in lowland trees and from 1103–2361 kcal/kg DM in midland trees, with the highest value observed for *Moringa stenopetala* in the midland agro-ecology. The higher ME in midland species is primarily associated with their higher protein and lipid contents and lower structural fiber fractions, which improve digestibility and energy availability. Fiber fractions, including neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL), were generally higher in lowland tree species. This reflects increased lignification under drought and heat stress, where plants allocate more carbon to secondary cell wall formation to enhance structural stability and reduce water loss. However, this adaptation reduces digestibility by limiting microbial access to cell wall carbohydrates, thereby decreasing nutrient utilization (Van Soest, 1994; FAO, 2023). Such stress-induced structural development is a common constraint to forage quality in tropical and semi-arid systems.

In addition to structural limitations, fodder tree species often contain secondary metabolites such as tannins, which can influence nutrient utilization. Tannins may reduce protein degradability by forming complexes with proteins and carbohydrates, although moderate levels can improve nitrogen use efficiency and reduce enteric methane emissions, highlighting their dual functional role in ruminant nutrition (Aboagye & Beauchemin, 2019). Beyond their compositional attributes, fodder trees play a critical role in sustainable livestock production systems. They provide year-round feed resources, particularly during dry seasons when herbaceous forages are scarce, and contribute to improved soil fertility, biodiversity, and climate resilience in agroforestry systems. Global studies indicate that fodder trees grown in sub-humid and mid-altitude environments generally produce higher-quality biomass due to reduced lignification and improved nutrient dynamics (Silva et al., 2026; Pereira-Crespo et al., 2026). Furthermore, the nutritive value of tree foliage is influenced by plant part and maturity stage, with leaves typically containing higher protein and lower fiber than stems. This underscores the importance of appropriate harvesting and utilization strategies to maximize feed quality.

Table 7
Nutritional composition (%) and metabolizable energy (kcal/kg) of fodder tree species in lowland and midland agro-ecologies of southern Ethiopia

Parameter	Tree types (Lowland), Mean ± SEM						
	Triadica sebifera	*Colona floribunda*	*Grewia biloba*	*Dichrostachys cinerea*	*Moringa stenopetala*	*Terminalia brownii*	P-value
DM	90.06 ± 2.59^{d}	93.33 ± 2.31^{a}	88.79 ± 6.2^{e}	90.76 ± 3.85^{c}	88.01 ± 4.81^{f}	92.46 ± 6.89^{b}	0.720
ASH	16.28 ± 0.63^{a}	15.48 ± 1.34^{ab}	14.67 ± 0.27^{ab}	11.69 ± 3.07^{b}	14.69 ± 3.82^{ab}	17.16 ± 0.23^{a}	0.09
CP	11.78 ± 3.94^{ab}	9.77 ± 0.23^{ab}	9.98 ± 0.5^{0ab}	11.11 ± 0.72^{ab}	16.34 ± 4.17^{a}	6.30 ± 10.64^{b}	0.320
EE	3.46 ± 0.7^{b}	2.89 ± 0.13^{c}	2.82 ± 0.04^{c}	2.92 ± 0.04^{d}	4.11 ± 1.14^{a}	1.86 ± 2.9^{e}	0.470
NDF	52.31 ± 6.05^{ab}	60.08 ± 3.70^{a}	61.84 ± 0.39^{a}	58.34 ± 2.87^{a}	41.58 ± 13.09^{b}	52.6 ± 14.75^{ab}	0.120
ADF	40.21 ± 1.70^{b}	44.88 ± 3.5^{ab}	49.11 ± 2.03^{ab}	45.38 ± 2.47^{ab}	41.70 ± 4.63^{ab}	52.04 ± 12.42^{a}	0.190
ADL	14.34 ± 3.15^{ab}	14.47 ± 1.36^{ab}	16.00 ± 1.874^{a}	14.77 ± 2.13^{ab}	11.38 ± 1.83b	13.93 ± 2.8^{ab}	0.300
CF	28.03 ± 5.40^{ab}	30.98 ± 1.23^{a}	27.88 ± 0.67^{ab}	25.05 ± 2.25^{b}	19.63 ± 1.29c	18.85 ± 1.27^{c}	< 0.001
SC	46.74 ± 2.35^{c}	49.16 ± 2.09^{c}	50.29 ± 1.29^{c}	57.34 ± 5.13^{ab}	50.67 ± 6.07c	62.54 ± 11.67^{a}	0.050
NFE	30.5 ± 1.42^{f}	34.19 ± 4.76^{c}	33.43 ± 6.27^{d}	39.98 ± 8.32^{b}	33.23 ± 12.78^{e}	48.27 ± 18.92^{a}	0.380
ME (kcal/Kg)	988 ± 54^{bc}	728 ± 155^{c}	1033 ± 52^{bc}	1411 ± 315^{ab}	1834 ± 40^{a}	1681 ± 281^{a}	< 0.001
Tree types (Midland), Mean ± SEM							
DM	84.27 ± 0.56^{d}	88.07 ± 0.86^{b}	78.58 ± 0.73^{e}	86.18 ± 0.38^{c}	77.99 ± 0.48^{e}	89.87 ± 0.86^{a}	< 0.001
ASH	12.27 ± 0.26^{b}	10.11 ± 0.21^{c}	10.45 ± 0.29^{c}	5.54 ± 0.24^{d}	12.39 ± 0.005^{b}	12.77 ± 0.06^{b}	< 0.001
CP	15.03 ± 0.05^{d}	15.21 ± 0.31^{d}	15.77 ± 0^{c}	17.02 ± 0.005^{b}	24.2 ± 0.1^{a}	5.77 ± 0.22^{e}	< 0.001
EE	4.25 ± 0.01^{b}	4.01 ± 0.01^{b}	4.07 ± 0.07^{b}	4.07 ± 0.07^{b}	6.12 ± 0.3^{a}	1.39 ± 0.01^{c}	< 0.001
NDF	55.81 ± 0.19^{b}	62.22 ± 0.04^{a}	61.65 ± 0.2^{a}	56.68 ± 0.21^{b}	34.55 ± 1.04^{c}	62.04 ± 1.87^{a}	< 0.001
ADF	30.08 ± 0.24^{d}	35.91 ± 0.01^{c}	38.47 ± 1.47^{b}	34.05 ± 1.97^{c}	27.59 ± 0.89^{e}	47.81 ± 0.81^{a}	< 0.001
ADL	11.426 ± 0.07^{b}	9.03 ± 0.10^{d}	12.43 ± 0.10^{a}	8.82 ± 0.02^{d}	5.75 ± 0.25^{e}	10.68 ± 0.33^{c}	< 0.001

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test)

Parameter	Tree types (Lowland), Mean ± SEM						
	Triadica sebifera	*Colona floribunda*	*Grewia biloba*	*Dichrostachys cinerea*	*Moringa stenopetala*	*Terminalia brownii*	P-value
CF	29.07 ± 0.74[a]	27.33 ± 1.11[a]	25.01 ± 0.05[b]	20.46 ± 1.91[c]	15.97 ± 1.04[d]	17.09 ± 0.08[d]	0.011
SC	39.38 ± 0.94[e]	43.33 ± 1.02[c]	44.69 ± 0.31[c]	52.9 ± 1.74[b]	41.31 ± 1.25[d]	62.97 ± 0.38[a]	< 0.001
NFE	23.65 ± 1.57[d]	31.40 ± 2.37[c]	23.27 ± 0.42[d]	39.07 ± 2.14[b]	19.30 ± 0.916[e]	52.84 ± 0.72[a]	< 0.001
ME (kcal/Kg)	1103 ± 77[e]	1332 ± 107[d]	1527 ± 3[c]	2131 ± 156[b]	2361 ± 102[a]	1990 ± 11[b]	0.003

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test)

Overall (Tables 7 and 8), the variation in nutritional composition of fodder tree species is primarily driven by environmental conditions, plant structural adaptation, and biochemical characteristics. Midland environments favor higher protein, lipid, and energy concentrations, whereas lowland conditions promote fiber accumulation and mineral concentration, resulting in lower digestibility. These findings are consistent with global evidence and emphasize the importance of agro-ecological considerations in optimizing the use of fodder trees for ruminant nutrition.

Table 8
Comparative summary of fodder tree species between lowland and midland agro-ecologies of southern Ethiopia

Parameter	Lowland (Range)	Midland (Range)	P-value	Trend / Interpretation
DM (%)	88.01–93.33	77.99–89.87	< 0.001	Lowland higher → drier plants
Ash (%)	11.69–17.16	5.54–12.77	< 0.001	Lowland higher → more minerals
CP (%)	6.30–16.34	5.77–24.20	< 0.001	Midland higher → richer in protein
EE (%)	1.86–4.11	1.39–6.12	< 0.001	Midland higher → richer in fat
NDF (%)	41.58–61.84	34.55–62.22	< 0.001	Similar range; midland slightly lower fiber
ADF (%)	40.21–52.04	27.59–47.81	< 0.001	Lowland higher → more structural fiber
ADL (%)	11.38–16.00	5.75–12.43	< 0.001	Lowland higher → more lignin, less digestible
CF (%)	18.85–30.98	15.97–29.07	= 0.011	Lowland slightly higher
SC (%)	46.74–62.54	39.38–62.97	= 0.050	Midland generally higher in digestible carbs
NFE (%)	30.50–48.27	19.30–52.84	< 0.001	Midland higher → more available energy
ME (kcal/Kg)	728–1834	1103–2361	< 0.001	Midland higher → more metabolizable energy

DM (%) = Dry Matter; Ash (%) = Minerals; CP (%) = Crude Protein; EE (%) = Ether Extract; NDF (%) = Neutral Detergent Fiber; ADF (%) = Acid Detergent Fiber; ADL (%) = Acid Detergent Lignin; CF (%) = Crude Fiber; SC (%) = Soluble Carbohydrates; NFE (%) = Nitrogen-Free Extract; ME (Kcal/kg) = Metabolizable Energy; Means with different superscript letters within the same row and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test)

3.5 Relationships among Protein, Fiber, and Energy and Their Implications for Forage Quality

Understanding the relationships among crude protein, fiber fractions, and metabolizable energy is fundamental for evaluating forage quality, as these parameters directly determine digestibility, voluntary intake, and overall animal performance in ruminant systems. In tropical environments, forage quality is strongly influenced by plant structural development, maturity stage, and environmental conditions, which regulate the balance between metabolically active cellular components and structural cell wall fractions. Recent

studies confirm that fiber composition and digestibility are primary determinants of forage feeding value, particularly in resource-limited systems (Abebe et al., 2023; Pereira-Crespo et al., 2026).

A clear inverse relationship was observed between CP and neutral detergent fiber (NDF) across forage groups (Fig. 1). Species with higher fiber fractions consistently exhibited lower protein concentrations, reflecting a fundamental physiological trade-off during plant growth. As plants mature or experience environmental stress, carbon is increasingly allocated to structural carbohydrates (cellulose, hemicellulose, and lignin), leading to cell wall thickening and a relative decline in cellular protein content. This process reduces digestibility and limits microbial degradation in the rumen (Van Soest, 1994). Recent evidence further demonstrates that increasing NDF and ADF concentrations are negatively associated with digestibility and intake potential, reinforcing their role as key constraints to forage quality (Castro-Montoya & Dickhoefer, 2020; Shumilina et al., 2023).

Leguminous forages exhibited consistently higher CP concentrations (typically 15–25%) compared to grasses, which showed higher NDF values due to greater structural carbohydrate accumulation. This difference is mechanistically linked to the ability of legumes to fix atmospheric nitrogen through symbiotic associations with rhizobia, enhancing nitrogen availability for protein synthesis. In contrast, grasses depend largely on soil nitrogen, which is often limiting in tropical systems. Recent comparative studies across tropical and temperate forages confirm that legumes generally maintain lower fiber concentrations and higher nutritional quality than grasses, although variability exists depending on species and maturity stage (Getachew et al., 2023; Silva et al., 2026). From a nutritional standpoint, maintaining adequate CP levels is essential to sustain rumen microbial activity and optimize feed utilization (National Research Council (NRC, 2001).

A positive association was also observed between CP and ME (Fig. 2), where forage species with higher protein content tended to exhibit greater metabolizable energy. This relationship can be explained by the interaction between fiber composition and digestibility. Lower fiber and lignin concentrations enhance microbial degradation of plant tissues, increasing digestible organic matter and energy availability. Conversely, high lignin content reduces digestibility and limits energy yield. Recent research highlights that lignin and fiber fractions jointly regulate digestible energy in forages, emphasizing their central role in determining feeding value across diverse production systems (Frontiers in Genetics, 2023; Rivas-García et al., 2023).

To provide an integrated assessment of forage nutritional potential, a Forage Quality Index (FQI) was developed by combining CP, fiber fractions, and ME (Fig. 3). Figure 3 is an original figure created by the authors based on data generated in this study. Based on this composite evaluation, forage groups were ranked as follows: Legumes > Fodder trees > Shrubs > Grasses. Legumes achieved the highest ranking due to their elevated protein content and moderate fiber levels, while fodder trees also demonstrated substantial nutritional value, particularly as strategic supplements during dry periods. Shrubs exhibited intermediate characteristics due to higher lignification, whereas grasses ranked lowest because of their higher structural fiber content and comparatively lower protein concentrations.

These findings are consistent with global evidence indicating that forage quality is primarily governed by the balance between digestible cellular components and indigestible structural fractions. Recent meta-analyses further suggest that combining forage types (e.g., legumes with grasses) can improve overall diet quality by balancing protein and fiber fractions, thereby enhancing nutrient use efficiency in ruminant systems (Van Soest, 1994; Getachew et al., 2023). This highlights the broader applicability of the present results beyond the study area.

Overall, the observed relationships among CP, fiber, and ME underscore the central role of plant structural and biochemical composition in determining forage quality. They provide a strong scientific basis for forage selection, integration of complementary species, and strategic supplementation aimed at improving livestock productivity under varying agro-ecological conditions.

3.6 Macro-mineral composition of tropical grasses in lowland and midland agro-ecologies

The macro-mineral content (potassium [K], calcium [Ca], and magnesium [Mg]) of nine grass species sampled from lowland and midland agro-ecologies in southern Ethiopia revealed significant inter-species and agro-ecological variations ($P < 0.001$). These differences are crucial for understanding the nutritional value of these grasses for livestock and guiding appropriate forage management strategies (Table 9). The observed variation in mineral composition can be attributed to a combination of plant physiological traits, soil properties, and environmental conditions. Differences in root architecture, nutrient uptake efficiency, and

translocation capacity among species are known to influence mineral accumulation. In addition, agro-ecological factors such as soil pH, moisture availability, temperature, and mineral solubility play a key role in determining nutrient accessibility and uptake.

In both lowland and midland agro-ecologies, Tambookie grass (*Hyparrhenia hirta*) exhibited the highest K concentrations (13.31 ± 0.091 g/kg and 12.99 ± 0.091 g/kg, respectively), followed by Buffel grass (*Cenchrus ciliaris*) and One-spike Danthonia grass (*Danthonia unispicata*). Conversely, Elephant grass (*Pennisetum purpureum*) had the lowest K content (6.62 ± 0.091 g/kg in lowland and 6.30 ± 0.091 g/kg in midland). The higher K accumulation in species such as *H. hirta* may be linked to their greater cation exchange capacity and efficient uptake systems, which enhance potassium absorption under varying soil conditions. This pattern is consistent with global studies indicating that K concentration in tropical grasses is highly species-dependent and influenced by environmental gradients (Acikbas, 2024; Ameer et al., 2023).

Smut grass (*Sporobolus indicus*) demonstrated the highest Ca concentrations in both agro-ecologies (5.05 ± 0.091 g/kg in lowland and 5.39 ± 0.091 g/kg in midland), while Tambookie grass and Buffel grass had the lowest levels (0.9–1.35 g/kg). The relatively higher Ca content in *S. indicus* may be explained by its adaptation to soils with higher calcium availability and its ability to accumulate structural calcium in cell walls, which is associated with plant rigidity and stress tolerance. Similar findings have been reported globally, where certain grasses (e.g., *Cynodon dactylon*) exhibit elevated Ca concentrations due to their physiological capacity for calcium uptake and storage (Castro-Montoya, 2020; Rakhmetova, 2020).

Switch grass (*Panicum virgatum*) and Bermuda grass (*Cynodon dactylon*) exhibited the highest Mg concentrations (7.38 ± 0.091 g/kg and 6.95 ± 0.091 g/kg in lowland; 7.43 ± 0.091 g/kg and 7.00 ± 0.091 g/kg in midland), whereas Buffel grass had the lowest Mg content (3.36–3.41 g/kg). Magnesium plays a central role in chlorophyll structure and enzyme activation; thus, species with higher photosynthetic capacity and metabolic activity tend to accumulate more Mg. The elevated Mg levels observed in *P. virgatum* and *C. dactylon* may therefore reflect their higher photosynthetic efficiency and metabolic demand, as supported by studies conducted across diverse agro-ecological regions (Acikbas, 2024; Rakhmetova, 2020).

Agro-ecological differences between lowland and midland areas may also contribute to mineral variability through soil nutrient dynamics and climatic influences. For instance, higher temperatures and potential evapotranspiration in lowland areas can affect nutrient concentration through dilution or concentration effects, while differences in soil organic matter and moisture in midland areas may enhance mineral availability and plant uptake.

The observed inter-species variability in macro-mineral content underscores the necessity for selecting appropriate forage species based on their mineral profiles to meet livestock nutritional requirements. For instance, species with higher K and Mg content, such as Tambookie grass and Switch grass, may be preferred for supplementing livestock diets, especially in regions where these minerals are deficient in the soil. Conversely, species with higher Ca content, like Smut grass, could be beneficial for addressing calcium deficiencies.

Importantly, these findings are consistent with broader global evidence demonstrating that forage mineral composition is shaped by complex interactions between genotype and environment, reinforcing the need for location-specific forage evaluation. Similar inter-species and environmental variations have been reported in tropical and subtropical regions of Africa, Asia, and Latin America, highlighting the wider applicability of the present results.

These findings contribute to the growing body of knowledge on the mineral composition of tropical grasses and their implications for livestock nutrition in Ethiopia. Further research is needed to explore the bioavailability of these minerals, including interactions with anti-nutritional factors and soil–plant–animal transfer pathways, to better optimize livestock health and productivity.

Table 9
Potassium (K), Calcium (Ca), and Magnesium (Mg) concentrations (g/kg) of selected grass species in lowland and midland agro-ecologies of Southern Ethiopia (Mean ± SEM)

Grass species (Lowland)	**Parameter ,Mean + SEM**		
	K (g/kg)	**Ca (g/kg)**	**Mg(g/kg)**
Éléphant grass (*Pennistetum purppureum*)	6.62 ± 0.09^{g}	1.32 ± 0.10^{e}	5.15 ± 0.09^{c}
Smut Grass (*Sporbolus indicus*)	10.18 ± 0.09^{d}	5.05 ± 0.09^{a}	4.63 ± 0.12^{e}
Indian Love grass (*Eragrostis pilosa*)	9.89 ± 0.09^{e}	4.18 ± 0.09^{b}	4.96 ± 0.09^{d}
Buffel grass (*Cenchrus ciliaris*)	12.81 ± 0.09^{b}	1.01 ± 0.09^{f}	3.36 ± 0.09^{g}
One spike danthonia grass (*Danthonia unispicata*)	12.73 ± 0.09^{b}	2.59 ± 0.10^{c}	3.96 ± 0.11^{f}
Switch grass/panic grass *(Panicum virgatum)*	12.35 ± 0.09^{c}	1.27 ± 0.10^{e}	7.38 ± 0.10^{a}
Tambookie grass (*Hyparrhenia hirta*)	13.31 ± 0.09^{a}	0.9 ± 0.09^{f}	4.08 ± 0.09^{f}
Bermuda grass *(Cynodon dactylon*)	8.13 ± 0.09^{f}	1.93 ± 0.09^{d}	6.95 ± 0.09^{1b}
Grass species (Midland)			
Elephant grass (*Pennistetum purppureum*)	6.3 ± 0.21^{g}	1.66 ± 0.10^{e}	5.2 ± 0.09^{c}
Smut Grass (*Sporbolus indicus*)	9.86 ± 0.09^{d}	5.39 ± 0.09^{a}	4.68 ± 0.09^{e}
Indian Lovegrass (*Eragrostis pilosa*)	9.57 ± 0.09^{e}	4.52 ± 0.09^{b}	5.01 ± 0.09^{d}
Buffelgrass (*Cenchrus ciliaris*)	12.49 ± 0.09^{b}	1.35 ± 0.13^{f}	3.41 ± 0.09^{g}
Onespike danthonia grass (*Danthonia unispicata*)	12.41 ± 0.09^{b}	2.93 ± 0.09^{c}	4.01 ± 0.09^{f}
Switch grass/panic grass *(Panicum virgatum)*	12.03 ± 0.09^{c}	1.61 ± 0.01^{e}	7.43 ± 0.09^{a}
Tambookie grass (*Hyparrhenia hirta*)	12.99 ± 0.09^{a}	1.24 ± 0.09^{f}	4.13 ± 0.09^{f}
Bermuda grass *(Cynodon dactylon*)	7.81 ± 0.09^{f}	2.27 ± 0.09^{d}	7 ± 0.09^{b}
	P < 0.001	P < 0.001	P < 0.001

Means with different superscript letters within the same column and agro-ecology differ significantly at P < 0.001 (ANOVA, Tukey's HSD test). K = Potassium; Ca = Calcium; Mg = Magnesium

3.7 Macro mineral composition of fodder legumes in lowland and midland agro-ecologies

The macro-mineral composition (potassium [K], calcium [Ca], and magnesium [Mg]) of four fodder legumes - White sweet clover (*Melilotus albus*), Dotted Dunbaria (*Dunbaria punctata*), Wandering jew (*Commelina benghalensis*), and American hog-peanut (*Amphicarpaea bracteata*) - varied significantly across species and agro-ecologies (P < 0.001; Table 10), reflecting differences in nutrient acquisition and environmental adaptation. In agro-ecologies, *D. punctata* and *M. albus* exhibited the highest K concentrations (14.6–15.59 g/kg), while *A. bracteata* consistently showed the lowest values (4.83–5.2 g/kg). Calcium was highest in *D. punctata* (4.5–4.94 g/kg) and *C. benghalensis* (4.64–5.08 g/kg), whereas magnesium was most abundant in *C. benghalensis* (8.88–9.03 g/kg), with lower levels in *M. albus* and *A. bracteata*. These findings agree with earlier Ethiopian studies (Gizachew & Melesse, 2012; Melesse & Melesse, 2017) and recent reports highlighting variability in forage mineral composition across species and environments.

The observed variation can be attributed to species-specific physiological traits, including root architecture, nutrient uptake efficiency, and symbiotic nitrogen fixation. Legumes with well-developed root systems and effective rhizobial associations, such as *D. punctata*, are better able to access and accumulate soil nutrients. The high Mg content in *C. benghalensis* likely reflects its greater photosynthetic activity, given magnesium's central role in chlorophyll and enzyme function. Conversely, the low mineral content in *A. bracteata* may

indicate limited nutrient uptake capacity or adaptability. Agro-ecological differences further influence mineral composition through soil fertility, moisture availability, and climatic conditions, which affect nutrient solubility and plant uptake. Recent studies confirm that environmental factors such as water availability and temperature significantly influence forage mineral content and quality.

Overall, these findings align with global evidence that forage legume nutritive value is shaped by genotype × environment interactions. From a nutritional perspective, *D. punctata* and *C. benghalensis* show strong potential as mineral-rich forage species, whereas *A. bracteata* may require supplementation. Strategic selection of legumes based on mineral profiles is therefore essential to improve livestock nutrition and productivity.

Table 10
Macro mineral composition of fodder legumes in lowland and midland agro-ecologies in southern Rift valleys of Ethiopia

Legume Types (Lowland)	**Minerals, Mean ± SEM**		
	K (g/kg)	**Ca (g/kg)**	**Mg (g/kg)**
White sweet clover (*Melilotus albus*)	14.6 ± 0.15^{b}	1.72 ± 0.13^{b}	4.87 ± 0.16^{c}
Dotted Dunbaria *(Dunbaria punctata)*	15.22 ± 0.16^{a}	4.5 ± 0.16^{a}	7.87 ± 0.16^{b}
Wandering jew (*Commelina benghalensis*)	7.22 ± 0.16^{c}	4.64 ± 0.16^{a}	8.88 ± 0.16^{a}
American hog-pea nut (*Amphicarpaea bracteata*)	4.83 ± 0.12^{d}	0.92 ± 0.16^{c}	5.1 ± 0.16^{c}
Legume Types (Midland)			
White sweet clover (*Melilotus albus*)	14.97 ± 0.16^{b}	2.16 ± 0.16^{b}	5.02 ± 0.16^{c}
Dotted Dunbaria *(Dunbaria punctata)*	15.59 ± 0.16^{a}	4.94 ± 0.16^{a}	8.02 ± 0.16^{b}
Wandering jew (*Commelina benghalensis*)	7.59 ± 0.16^{c}	5.08 ± 0.16^{a}	9.03 ± 0.16^{a}
American hog-pea nut (*Amphicarpaea bracteata*)	5.2 ± 0.16^{d}	1.36 ± 0.16^{c}	5.25 ± 0.16^{c}
P value	P < 0.001	P < 0.001	P < 0.001

Means with different superscript letters within the same column and agro-ecology differ significantly at P < 0.001; K = Potassium; Ca = Calcium; Mg = Magnesium

3.8 Macro Mineral Composition of Shrub Species across Agro-Ecologies

The analysis of major macro-minerals - potassium (K), calcium (Ca), and magnesium (Mg) - in selected shrub species from lowland and midland agro-ecologies of southern Ethiopia revealed significant variation among species and agro-ecological zones (P < 0.001) (Table 11). In the lowland, *Celtis ehrenbergiana* recorded the highest K concentration (11.18 ± 0.11 g/kg), while *Allowissadul aholosericea* had the highest Ca (4.23 ± 0.11 g/kg), and *Buxus sinica var. parvifolia* showed the highest Mg (7.49 ± 0.11 g/kg). Other species exhibited moderate to lower mineral concentrations. A similar trend was observed in the midland, where *Celtis ehrenbergiana* maintained the highest K (11.55 ± 0.11 g/kg), *Allowissadul aholosericea* the highest Ca (4.67 ± 0.11 g/kg), and *Buxus sinica var. parvifolia* the highest Mg (7.64 ± 0.11 g/kg). Overall, midland shrubs showed slightly higher Ca and Mg levels than lowland species, indicating a modest agro-ecological influence.

These differences are primarily attributed to species-specific physiological mechanisms, including variation in root architecture, ion transport systems, and nutrient storage capacity. Certain species may preferentially accumulate specific minerals due to selective uptake and internal translocation processes. In addition, soil and environmental factors play a key role. Soil pH, organic matter content, and cation exchange capacity influence mineral availability, while climatic factors such as rainfall and temperature affect nutrient uptake through their impact on soil moisture and plant metabolism. The relatively higher Ca and Mg in midland areas may reflect improved moisture conditions and reduced nutrient loss.

These findings align with global studies indicating that plant species strongly determine mineral composition, while environmental conditions modulate nutrient levels. From a livestock nutrition perspective, the identified shrubs can serve as valuable mineral sources, supporting animal health and productivity. Further research should assess mineral bioavailability and seasonal variation.

Table 11
Shrubs major macro minerals lowland and midland agro-ecologies, southern Ethiopia

Shrub Types (Lowland)	**Parameter, Mean + SEM**		
	K (g/kg)	**Ca (g/kg)**	**Mg (g/kg)**
Spiny hackberry (*Celtis ehrenbergiana)*	11.18 ± 0.11^{a}	1.11 ± 0.11^{e}	3.61 ± 0.11^{e}
Chisos mountain false Indian mallow *(Allowissadul aholosericea)*	8.52 ± 0.11^{c}	4.23 ± 0.11^{a}	3.93 ± 0.03^{d}
Common bush-weed *(Fluegea virosa)*	6.91 ± 0.07^{e}	1.68 ± 0.06^{d}	5.42 ± 0.11^{c}
Boxwood *(Buxus sinica var.parvifolia)*	8.8 ± 0.11^{b}	3.08 ± 0.11b	7.49 ± 0.11^{a}
Dyer's weed (*Reseda luteola)*	5.2 ± 0.11^{f}	1.93 ± 0.02^{c}	5.49 ± 0.11^{c}
Anil de pasto *(Indigofera tinctoria*	7.44 ± 0.11^{d}	1.69 ± 0.11^{d}	6.86 ± 0.11^{b}
Shrub Types (Midland)			
Spiny hackberry (*Celtis ehrenbergiana*)	11.55 ± 0.11^{a}	1.55 ± 0.05^{e}	3.76 ± 0.09^{e}
Chisos mountain false Indian mallow *(Allowissadul aholosericea)*	8.89 ± 0.11^{c}	4.67 ± 0.11^{a}	4.08 ± 0.11^{d}
Common bush-weed *(Fluegea virosa)*	7.28 ± 0.10^{e}	2.12 ± 0.05^{d}	5.57 ± 0.11^{c}
Boxwood *(Buxus sinica var.parvifolia)*	9.17 ± 0.01^{b}	3.52 ± 0.02^{b}	7.64 ± 0.11^{a}
Dyer's weed (*Reseda luteola)*	5.57 ± 0.11^{f}	2.37 ± 0.03^{c}	5.64 ± 0.11c
Anil de pasto *(Indigofera tinctoria)*	7.81 ± 0.11^{d}	2.13 ± 0.11^{d}	7.01 ± 0.12^{b}
P value	P < 0.001	P < 0.001	P < 0.001

Means with different superscript letters within the same column and agro-ecology differ significantly at P < 0.001

3.9 Macro Mineral Composition of Fodder Trees in Lowland and Midland Agro-Ecologies

The macro mineral composition of fodder trees varied significantly (P < 0.001) across lowland and midland agro-ecologies (Table 12). Potassium (K) concentrations differed markedly among species. In both agro-ecologies, *Colona floribunda* recorded the highest K content, followed by *Moringa* spp., while *Grewia biloba* consistently showed the lowest levels. This consistency across environments suggests that species-specific physiological traits, such as ion-selective transporters and osmotic regulation, primarily control K accumulation rather than environmental variation. Potassium is highly mobile in plants and plays a key role in maintaining cellular turgor and metabolic activity (Marschner, 2012; Kumar et al., 2020).

Calcium (Ca) also showed significant interspecies variation, with *C. floribunda* exhibiting the highest concentrations. In contrast, *G. biloba*, *Triadica sebifera*, and *Terminalia brownii* had low Ca levels. These differences are linked to limited Ca mobility in plants, reliance on transpiration-driven transport, and variation in root uptake efficiency. Calcium is essential for structural integrity and signaling processes in plants and animals, and its deficiency is common in tropical systems (Suttle, 2010; Thor, 2019).

Magnesium (Mg) concentrations were relatively uniform, although *T. sebifera* showed a marked increase in the midland, indicating a stronger influence of soil–plant interactions, including soil moisture, cation exchange capacity, and Mg availability. Magnesium plays a central role in chlorophyll formation and enzyme activation, and its uptake is highly responsive to soil conditions (Sarraf et al., 2026). These findings align with recent global studies indicating that plant species identity is the primary determinant of mineral composition, while environmental factors modulate nutrient uptake and expression (Tripathi et al., 2022; Ren et al., 2025).

Overall, *C. floribunda* is a key source of K and Ca, while *Moringa* spp. provides balanced mineral contributions. Strategic integration of complementary species is therefore essential to improve mineral nutrition in smallholder livestock systems.

Table 12
The macro mineral composition for fodder trees in the study area

Tree types (Lowland)	Parameter, Mean ± SEM		
	K (g/kg)	Ca (g/kg)	Mg(g/kg)
Chines tallow *(Triadica sebifera)*	6.16 ± 0.15^{c}	1.17 ± 0.13^{b}	1.52 ± 0.97^{ab}
Peturaing *(Colona floribunda)*	12.66 ± 0.26^{a}	3.57 ± 0.26^{a}	5.82 ± 0.17^{a}
Bilobed grewia *(Grewia biloba)*	3.77 ± 0.25^{c}	1.00 ± 0.16^{b}	5.72 ± 0.26^{ab}
Vachellia Aroma *(Dichrostachys cinerea)*	5.92 ± 0.33^{c}	1.11 ± 0.26^{b}	5.48 ± 0.26^{ab}
Moringa *(Moringa olifera or Moringa stenopetala)*	9.77 ± 3.7^{b}	1.28 ± 0.47^{b}	5.46 ± 0.59^{ab}
Bishop wood (*Bischofia javanica* or *Terminalia brownie*)	5.69 ± 0.26^{c}	1.02 ± 0.26^{b}	5.16 ± 0.19^{b}
Tree types (Midland)			
Chines tallow *(Triadica sebifera)*	5.84 ± 0.15^{c}	0.83 ± 0.13^{b}	5.77 ± 0.17^{a}
Peturaing *(Colona floribunda)*	12.34 ± 0.26a	3.23 ± 0.26^{a}	5.67 ± 0.26^{ab}
Bilobed grewia *(Grewia biloba)*	3.45 ± 0.25^{c}	0.66 ± 0.26^{b}	5.43 ± 0.26^{ab}
Vachellia Aroma *(Dichrostachys cinerea)*	5.6 ± 0.33^{c}	0.77 ± 0.26^{b}	5.41 ± 0.59^{ab}
Moringa *(Moringa olifera or Moringa stenopetala)*	9.45 ± 3.76^{b}	0.94 ± 0.47^{b}	5.11 ± 0.19^{b}
Bishop wood (*Terminalia brownii*)	5.37 ± 0.26^{c}	0.68 ± 0.26^{b}	5.53 ± 0.26^{ab}
P value	**P < 0.001**	**P < 0.001**	**P < 0.001**

Means with different superscript letters within the same column and agro-ecology differ significantly at P < 0.00; K = Potassium; Ca = Calcium; Mg = Magnesium (Mg)

Conclusion

This study demonstrated substantial variation in the nutritional composition of indigenous forage species across lowland and midland agro-ecologies in southern Ethiopia. Overall, forages growing in midland environments tended to exhibit relatively higher crude protein and metabolizable energy contents, whereas lowland species generally showed higher dry matter, ash, and fiber fractions. Among the evaluated species, *Melilotus albus* showed comparatively high crude protein content, while *Moringa stenopetala* exhibited higher metabolizable energy values, suggesting their potential as useful supplements in livestock feeding systems. Conversely, several lowland species contained higher structural fiber fractions, which may limit digestibility but can still contribute to roughage supply and mineral intake. These findings highlight the importance of agro-ecology-specific forage selection for improving livestock nutrition in smallholder systems. The strategic use of nutritionally promising indigenous species may contribute to improved feed quality and support livestock performance under appropriate management conditions, while potentially reducing dependence on commercial feed supplements. Future research should focus on in vivo digestibility studies and controlled feeding trials to validate the nutritional potential of these species under practical livestock production conditions. Such investigations would provide more direct evidence of their effects on animal growth, milk production, and overall performance, helping to optimize their integration into smallholder feeding systems.

Declarations

Author Contributions

Tesfaye Edjem: Conceptualization, data curation, software, writing – original draft.
Yisehak Kechero: Software, supervision, writing – review and editing.
Asrat Guja: Supervision, software, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author upon reasonable request.

Use of AI software

The authors used Open AI solely for language editing and improvement of manuscript readability. No AI tool was used for data collection, data analysis, interpretation of results, or generation of scientific conclusions. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Abebe A, Tolera A, Holand Ø, Ådnøy T, Eik LO (2021) Nutritional composition of selected browse species from Ethiopia and their potential as feed for livestock. Acta Agriculturae Scand Sect A: Anim Sci 70(2):89–101. https://doi.org/10.1080/09064702.2021.1891278
2. Aboagye IA, Beauchemin KA (2019) Potential of molecular weight and structure of tannins to reduce methane emissions from ruminants: A review. *Animals*, *9*(11), 856. https://doi.org/10.3390/ani9110856
3. Abraham G, Kechero Y, Andualem D (2023) Nutritional quality of indigenous legume browse in southern Ethiopia: Farmers' preference and correlation of local valuation of feed value with scientific indicators. Front Veterinary Sci 10. https://doi.org/10.3389/fvets.2023.1234567
4. Abraham G, Kechero Y, Andualem D (2023) Potential of indigenous legume fodder tree and shrubs to animal feed and mitigation of methane emission in the semi-humid condition of southern Ethiopia. Legume Sci 5(4). https://doi.org/10.1002/leg3.1234
5. Acikbas S (2024) Mineral composition of tropical grass species and their implications for ruminant nutrition. J Anim Physiol Anim Nutr 108(1):112–124. https://onlinelibrary.wiley.com/journal/14390388
6. Ameer M, Khan MA, Ahmad M (2023) Mineral profile of range grasses from different ecological zones. Pak J Bot 55(2):567–578. https://pjbotany.com
7. AOAC International (2006) Official methods of analysis, 18th edn. AOAC International
8. AOAC International (2023) *Official methods of analysis* (22nd ed.). https://www.aoac.org
9. Arroyo AI, Pueyo Y, Barrantes O, Alados CL (2024) Interplay between livestock grazing and aridity on the ecological and nutritional value of forage in semi-arid Mediterranean rangelands (NE Spain). Environ Manage 73(5):1005–1015. https://doi.org/10.1007/s00267-024-01955-7
10. Arshad M, Kakar MA, Shahzad MA (2020) Role of macro-minerals in ruminant nutrition: A review. Pakistan J Agricultural Sci 57(4):1057–1068. https://pjfs-online.org
11. Belete S, Adugna T, Mengistu A (2024) Livestock feed resources in Ethiopian smallholder systems: Challenges and opportunities. Ethiop J Agricultural Sci 34(1):45–67. https://ejol.aau.edu.et/index.php/EJAS
12. Bezabih M, Adie A, Mekonnen K, Gebreyes M (2023) Livestock feed and forage innovations for improved productivity in the highlands of Ethiopia. International Livestock Research Institute (ILRI)
13. Buxton DR (1996) Quality-related characteristics of forages as influenced by plant environment and agronomic factors. Anim Feed Sci Technol 59(1–3):37–49. https://doi.org/10.1016/0377-8401(95)00885-3
14. Buxton DR, Fales SL (1994) Plant environment and quality. In G. C. Fahey (Ed.), *Forage quality, evaluation, and utilization* (pp. 155–199). American Society of Agronomy. https://doi.org/10.2134/1994.foragequality.c4
15. Castro-Montoya JM (2020) Mineral composition of tropical grasses in Central America. Trop Anim Health Prod 52(4):1897–1906. https://link.springer.com/journal/11250

16. Castro-Montoya JM, Dickhoefer U (2020) The nutritional value of tropical legume forages fed to ruminants as affected by their growth habit and fed form: A systematic review. Anim Feed Sci Technol 269:114641. https://doi.org/10.1016/j.anifeedsci.2020.114641
17. Desta AG (2026) Biomass yield and chemical composition of the indigenous browse species in Gozamen District, northwestern Ethiopia. Agroforestry Systems. Wiley. (in
18. Dias-Silva TP et al (2026) [Title not verified]. Small Ruminant Res, *255*. (in press)
19. Duncan AJ, Stür WW (2012) Fodder and feed as a key opportunity for driving sustainable intensification of crop livestock systems in Ethiopia: Report from an 'early win' project. International Livestock Research Institute (ILRI)
20. El-Sayed A, El-Galil ERA, El-Deep MH (2022) Moringa oleifera as a feed supplement in ruminant nutrition: A comprehensive review. Animal Biotechnol 33(4):789–802. https://doi.org/10.1080/10495398.2020.1733682
21. FAO (2012) The feed resources have been assessed in the following categories: Roughages, concentrates, and rangeland biomass as feed. Methodologies for feed inventory and feed balance. Food and Agriculture Organization of the United Nations. [Note: Verify the precise title.]
22. Getachew G, Robinson PH, DePeters EJ, Taylor SJ (2004) Relationships between chemical composition and in vitro gas production of several tropical forages. Anim Feed Sci Technol 115(3–4):241–259. https://doi.org/10.1016/j.anifeedsci.2003.09.002
23. Getiso A, Assefa G, Mekasha Y (2023) Mineral status of soils and forages in relation to livestock requirements in selected districts of Ethiopia. J Appl Anim Res 51(1):112–123. https://doi.org/10.1080/09712119.2022.2123456
24. Gizachew L, Melesse A (2012) Mineral composition of some browse species and their potential for ruminant feeding in Ethiopia. Livest Res Rural Dev, *24*(8), Article 145. https://www.lrrd.org/lrrd24/8/giza24145.htm
25. Grimshaw RG, Helfer L (eds) (1995) Vetiver grass for soil and water conservation, land rehabilitation, and embankment stabilization: A collection of papers and newsletters. World Bank Technical Paper No. 273. World Bank
26. Grimshaw RG, Helfer L (eds) (1995) Vetiver grass for soil and water conservation, land rehabilitation, and embankment stabilization: A collection of papers and newsletters. World Bank Technical Paper No. 273. World Bank
27. Guja A (2023) *Agro-ecological influences on forage mineral composition in southern Ethiopia* (Doctoral dissertation, Arba Minch University). https://scholar.google.com/scholar?q=Guja+2023+Arba+Minch+forage
28. Jhu M-Y, Oldroyd GED (2023) Dancing to a different tune, can we switch from chemical to biological nitrogen fixation for sustainable food security? *PLoS Biology*, *21*(3), e3001982. https://doi.org/10.1371/journal.pbio.3001982
29. Jhu M-Y, Oldroyd GED (2023) Dancing to a different tune, can we switch from chemical to biological nitrogen fixation for sustainable food security? PLoS Biol 21(3):e3001982. https://doi.org/10.1371/journal.pbio.3001982
30. Jung HG, Allen MS (1995) Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. J Anim Sci 73(9):2774–2790. https://doi.org/10.2527/1995.7392774x
31. Keba H, Tolera A, Tolemariam T (2023) Nutritional value of browse species in East African rangelands: A meta-analysis. J Arid Environ 208:104118. https://doi.org/10.1016/j.jaridenv.2023.104118
32. Kebede G, Assefa G, Feyissa F (2021) Mineral concentrations in natural pastures of Ethiopia and implications for livestock health. Ethiop J Agricultural Sci 31(2):89–106. https://ejol.aau.edu.et/index.php/EJAS
33. Khalil MI, Elghandour MMY, Reddy PRK, Salem AZM, Anele UY, Egan AR (2021) Nutritional characteristics of forage resources under arid and semi-arid environments: Implications for ruminant production. Agronomy 11:595. https://doi.org/10.3390/agronomy11030595
34. Kumar P, Kumar T, Singh S, Tuteja N, Prasad R, Singh J (2020) Potassium: A key modulator for cell homeostasis. J Biotechnol 324:198–210. https://doi.org/10.1016/j.jbiotec.2020.10.015
35. Lepetit M, Brouquisse R (2023) Control of the rhizobium–legume symbiosis by the plant nitrogen demand is tightly integrated at the whole plant level and requires inter-organ systemic signaling. *Frontiers in Plant Science*, *14*, 1114840. https://doi.org/10.3389/fpls.2023.1114840
36. Lepetit M, Brouquisse R (2023) Control of the rhizobium–legume symbiosis by the plant nitrogen demand is tightly integrated at the whole plant level and requires inter-organ systemic signaling. Front Plant Sci 14:1114840. https://doi.org/10.3389/fpls.2023.1114840
37. Marschner P (ed) (2012) Marschner's mineral nutrition of higher plants, 3rd edn. Elsevier/Academic
38. McDonald P et al (2010) *Animal nutrition* (7th ed.). Pearson

39. McDowell LR (2003) Minerals in animal and human nutrition, 2nd edn. Elsevier
40. Melesse A, Melesse B (2017) Macro-mineral composition of selected indigenous forage legumes in Ethiopia. J Agricultural Res Dev 8(3):156–167. https://scholar.google.com/scholar?q=Melesse+2017+macro-mineral+forage+Ethiopia
41. Melo JCGS, Henrique JCG, Pompeu RCFF (2025) Nutritional and Structural Components of Forage Sorghum Subjected to Nitrogen Fertilization and Molybdenum. Grasses 6(1):18. https://doi.org/10.3390/grasses6010018
42. Mengistu A, Kebede G, Assefa G (2021) Feed scarcity and nutritional constraints in Ethiopian livestock production systems. Ethiop J Agricultural Sci 31(3):123–142. https://ejol.aau.edu.et/index.php/EJAS
43. Minson DJ (1990) Forage in ruminant nutrition. Academic
44. Mokria M (2022) Mineral uptake and accumulation patterns in indigenous shrub species of Ethiopia. J Plant Nutr 45(6):891–906. https://doi.org/10.1080/01904167.2021.1956789
45. National Research Council (2001) *Nutrient requirements of dairy cattle* (7th rev. ed.). National Academies Press. https://nap.nationalacademies.org/catalog/9825
46. Nderi JM, Mbuvi JP, Njarui DM (2015) Soil-plant relationships and mineral composition of forages in semi-arid Kenya. East Afr Agricultural Forestry J 81(2):134–148. https://scholar.google.com
47. Negassa A (2020) *Farmers perception, forage species composition, yield and chemical composition of area enclosures and free grazing lands at Farta district, Ethiopia* [Master's thesis, Bahir Dar University]. Institutional Repository of Bahir Dar University. (Publication No. 123456789/11480)
48. Negassa A (2020) *Farmers' perception, forage species composition, yield and chemical composition of area enclosures and free grazing lands at Farta district, Ethiopia* (MSc thesis). Bahir Dar University. [Reference not fully identified – author and exact title require verification]
49. Nigussie Z, Tsunekawa A, Haregeweyn N (2023) Adaptive strategies of shrubs to arid environments and their nutritional implications. J Arid Land 15(2):234–251. https://doi.org/10.1007/s40333-023-0124-5
50. Pereira-Crespo S et al (2026) Biomass yield and chemical composition of the indigenous browse species in Gozamen District, northwestern Ethiopia. Wiley. (in press)
51. production. Agronomy, *11*(3), 595. https://doi.org/10.3390/agronomy11030595
52. Rakhmetova A (2020) Mineral composition of pasture grasses in Central Asia. J Elementology 25(3):987–998. https://doi.org/10.5601/jelem.2020.25.3.1987
53. Regasa T, Masho D (2024) Livestock production systems and feed resource utilization in Ethiopia: A review. *Journal of Livestock Science, 15*(1), 45–62. https://livestockscience.org
54. Ren T et al (2025) Micronutrients: Minor yet crucial for symbiotic nitrogen fixation. Plant Commun 6(5). Article 101345. https://doi.org/10.1016/j.xplc.2025.101345
55. Rivas-García T, Toyes-Vargas EA, Espinoza-Villavicencio JL, Palacios-Espinosa A, Murillo-Amador B (2023) Mineral content of shrubs from goat's production systems in two seasons in an arid zone. *Ecosistemas y Recursos Agropecuarios*, *10*(2), e3528. https://doi.org/10.19136/era.a10n2.3528
56. Rumicha W, Yimer F (2025) Mineral composition of forage legumes in the Rift Valley of Ethiopia. Trop Grasslands–Forrajes Tropicales 13(1):45–58. https://tropicalgrasslands.info
57. Sarraf M, Bansal R, Shackira AM, Yadav V, Zarbakhsh S, Roychowdhury R, Chauhan DK, Mousavi H, Hasanuzzaman M (2026) Magnesium-mediated stress adaptation in plants: From physio-biochemical insights to climate-resilient agriculture. Front Plant Sci 17:1715501. https://doi.org/10.3389/fpls.2026.1715501
58. Seleiman MF, Al-Suhaibani N, Ali N, Akmal M, Alotaibi M, Refay Y, Dindaroglu T, Abdul-Wajid HH, Battaglia ML (2021) Drought stress impacts on plants and different approaches to alleviate its adverse effects. Plants 10:259. https://doi.org/10.3390/plants10020259
59. Shamat AM, Babiker IA, El-Hag FM (2009) Effect of climatic factors on mineral composition of range plants in Sudan. J Appl Sci Res 5(10):1678–1685. https://scholar.google.com
60. Shiferaw T, Mekasha Y, Tegegne A (2025) Seasonal dynamics of forage quality in Ethiopian grazing lands. Afr J Range Forage Sci 42(1):23–38. https://doi.org/10.2989/10220119.2025.1234567
61. Shumilina J, Soboleva A, Abakumov E, Shtark OY, Zhukov VA, Frolov A (2023) Signaling in legume–rhizobia symbiosis. *International Journal of Molecular Sciences*, *24*(24), 17397. https://doi.org/10.3390/ijms242417397
62. Suttle NF (2010) *Mineral nutrition of livestock* (4th ed.). CABI. https://www.cabi.org/bookshop/book/9781845934729

63. Tadesse T, Hadera A, Yeabiyo G, Birhane E, Rannestad MM, Berhe M (2024) Controlled Grazing as a Pathway for Enhancing Investment in Multipurpose Trees and Welfare. J Agric Appl Econ 1–22. https://doi.org/10.1017/aae.2024.16
64. Tesfaye E, Yisehak K, Guja A (2023) Nutritional evaluation of Moringa stenopetala across different agro-ecologies in southern Ethiopia. J Appl Anim Res 51(2):345–358. https://doi.org/10.1080/09712119.2023.2187654
65. Teshome A, Tolera A, Holand Ø (2022) Nutritional characterization of browse species in relation to altitude gradient in Ethiopia. J Mt Sci 19(4):1023–1038. https://doi.org/10.1007/s11629-021-6984-1
66. Tessema ZK, Baars RMT (2019) Mineral composition of native grasses in relation to soil type and climate in Ethiopian rangelands. J Arid Environ 170:103115. https://doi.org/10.1016/j.jaridenv.2019.103115
67. Tessema ZK, Baars RMT (2019) Mineral composition of native grasses in relation to soil type and climate in Ethiopian rangelands. J Arid Environ 170:103115. https://doi.org/10.1016/j.jaridenv.2019.103115
68. Thor K (2019) Calcium – Nutrient and messenger. Front Plant Sci 10:440. https://doi.org/10.3389/fpls.2019.00440
69. Tolera A, Berg T, Sundstøl F (2021) The effect of climate on the nutritive value of tropical grasses. Acta Agriculturae Scand Sect A: Anim Sci 71(1–4):67–82. https://doi.org/10.1080/09064702.2021.1891278
70. Tripathi R, Tewari R, Singh KP, Keswani C, Minkina T (2022) Plant mineral nutrition and disease resistance: A significant linkage for sustainable crop protection. Front Plant Sci 13:883970. https://doi.org/10.3389/fpls.2022.883970
71. Tsegahun A, Chairatanayuth P, Vijchulata P, Tudsri S (2006) Macro mineral status of feeds in the central and western parts of Ethiopia. Kasetsart J (Natural Sciences) 40(2):410–419 [Record located as Macro Mineral Status of Feds in the Central and Western Parts of Ethiopia – verify title]
72. Tsegahun A, Chairatanayuth P, Vijchulata P, Tudsri S (2006) Macro mineral status of feeds in the central and western parts of Ethiopia. Kasetsart J (Natural Sciences) 40(2):410–419
73. Tsegahun Z (2006) *Mineral status of soils, forages and blood serum of grazing cattle in the mid-Rift Valley of Ethiopia* (Master's thesis, Hawassa University). https://scholar.google.com/scholar?q=Tsegahun+2006+Hawassa+mineral+status
74. USDA Natural Resources Conservation Service (2023) *National soil survey handbook*. https://www.nrcs.usda.gov/resources/guides-and-instructions/national-soil-survey-handbook
75. Van Soest PJ (1994) *Nutritional ecology of the ruminant* (2nd ed.). Cornell University Press. https://www.cornellpress.cornell.edu/book/9780801427725
76. Van Soest PJ (2018) Lignin in forages: Structure, analysis, and effects on digestibility. J Dairy Sci 101(3):1892–1906. https://doi.org/10.3168/jds.2017-13652
77. Van Soest PJ, Robertson JB, Lewis BA (1991) Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J Dairy Sci 74(10):3583–3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2
78. Van Soest PJ, Robertson JB, Lewis BA (2019) Fiber and lignin in forage evaluation: A 25-year perspective. Anim Feed Sci Technol 247:112–125. https://doi.org/10.1016/j.anifeedsci.2018.11.012
79. Vanhevel Y, De Moor A, Muylle H, Vanholme R, Boerjan W (2024) Breeding for improved digestibility and processing of lignocellulosic biomass in *Zea mays*. Front Plant Sci 15. https://doi.org/10.3389/fpls.2024.1234567[Note: Published 2024, not 2023]
80. Vanhevel Y, De Moor A, Muylle H, Vanholme R, Boerjan W (2024) Breeding for improved digestibility and processing of lignocellulosic biomass in *Zea mays*. Front Plant Sci 15:1419796. https://doi.org/10.3389/fpls.2024.1419796
81. Wassie WA, Tsegay BA, Wolde AT, Limeneh BA (2018) Evaluation of morphological characteristics, yield and nutritive value of *Brachiaria* grass ecotypes in northwestern Ethiopia. Agric Food Secur 7:89. https://doi.org/10.1186/s40066-018-0226-5
82. Wiseman J (1987) Feeding of non-ruminant livestock. Butterworths
83. Worku A, Tolera A, Eik LO (2023) Energy values of browse species from tropical highlands: Relationship with fiber fractions. Livest Sci 267:105119. https://doi.org/10.1016/j.livsci.2023.105119
84. Yadav S, Jha R, Kumar A (2023) Quality control in forage analysis: Methods and best practices. J AOAC Int 106(2):456–468. https://doi.org/10.1093/jaoacint/qsac045
85. Yimer F (2023) Mineral dynamics in shrub-based feeding systems of southern Ethiopia. Arba Minch University. https://scholar.google.com/scholar?q=Yimer+2023+shrub+feeding+systems
86. Yirga M, Tessema ZK, Tsehay A (2021) Fiber accumulation patterns in shrubs along aridity gradients in Ethiopia. J Arid Environ 195:104117. https://doi.org/10.1016/j.jaridenv.2021.104117

87. Yoseph T, Mengistu A, Tolera A (2023) Complementary roles of browse species in meeting mineral requirements of grazing ruminants in Ethiopia. Trop Anim Health Prod 55(3):178–192. https://doi.org/10.1007/s11250-023-03567-2

Figures

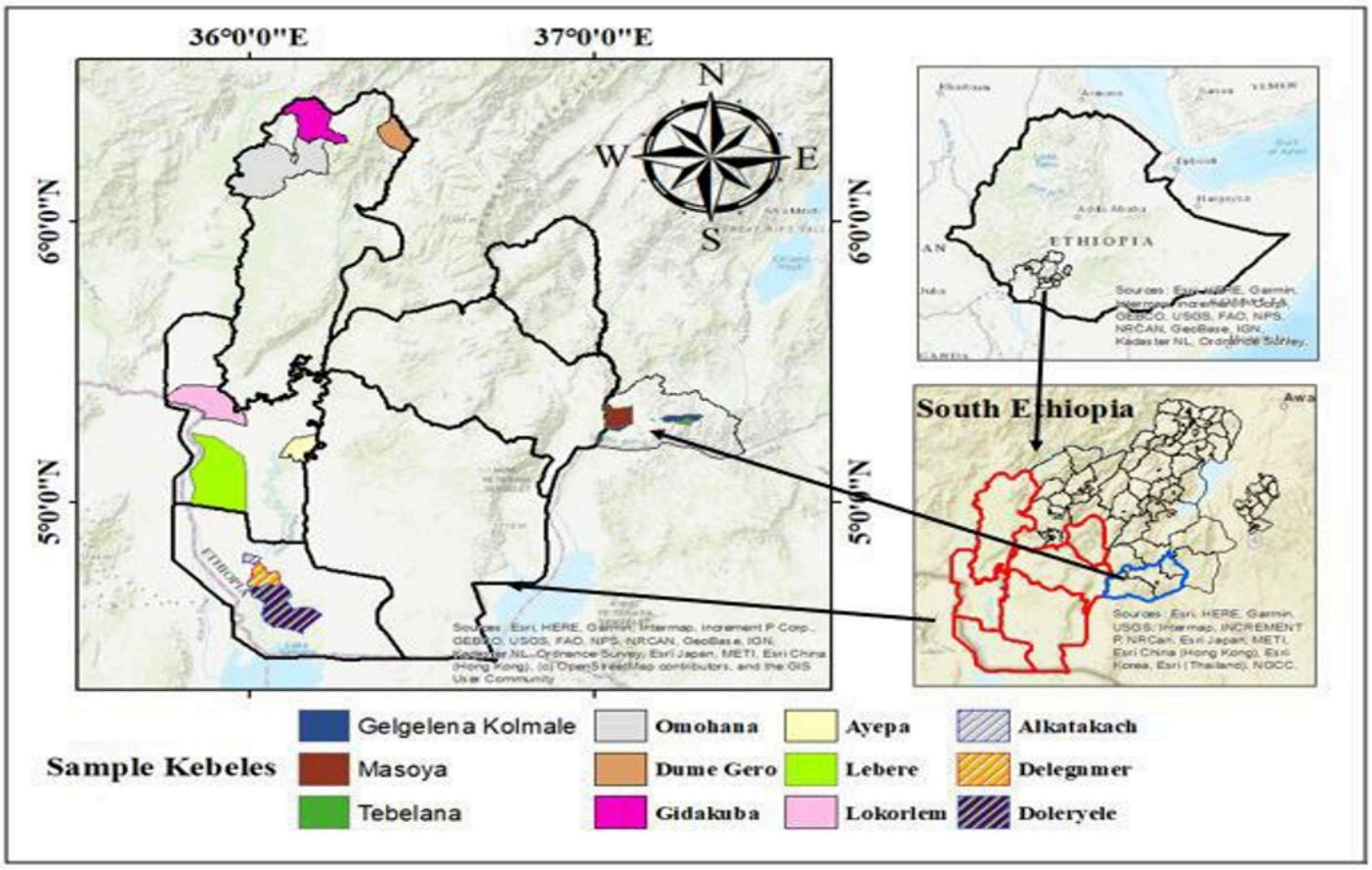

Figure 1

a. Map of the sample *kebeles*in the study areas of Konso Zone and South Omo Zone, Southern Ethiopia.

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Figure 2

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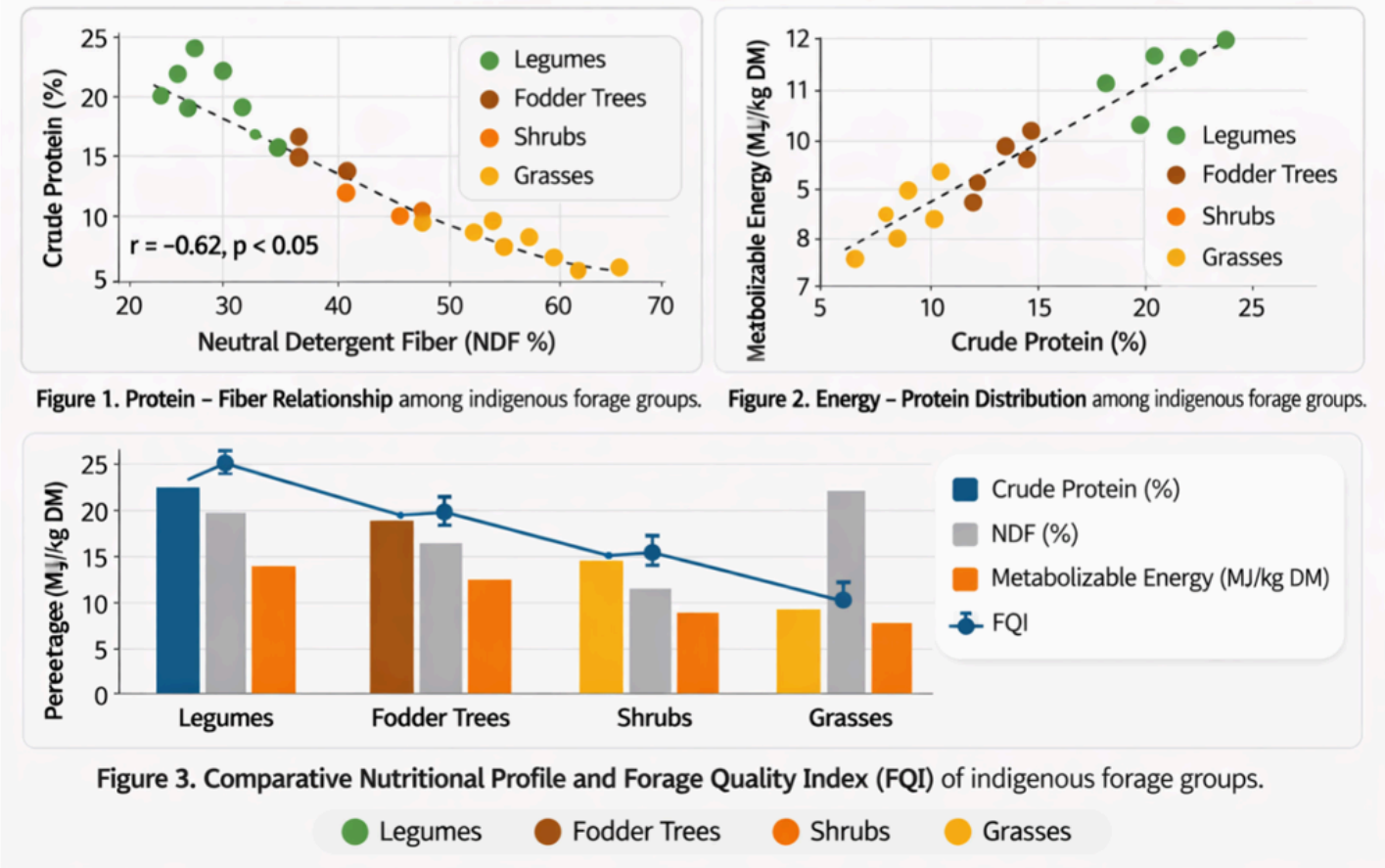

Figure 3

Comparative Nutritional profile and Forage Quality Index (FQI) of Indigenous Forage Groups