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Research Article

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Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11671461/v1

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Nutritional composition, phytochemical characteristics and *in vitro* digestibility of indigenous browse resources for Assam Hill goats in Northeast India

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Abstract

Indigenous browse resources may provide important nutrients for goats reared under smallholder production systems, particularly in tropical regions where the availability of conventional feed ingredients is limited. This study evaluated the nutritional composition, phytochemical characteristics and in vitro digestibility of eight indigenous browse resources collected from the Eastern Brahmaputra Valley of Assam, Northeast India, to assess their potential for Assam Hill goat feeding. Samples were analysed for proximate composition, fibre fractions, mineral content, secondary metabolites, in vitro dry matter digestibility (IVDMD) and in vitro organic matter digestibility (IVOMD). Crude protein (CP) concentration varied from 3.53 to 21.50%, with Gmelina arborea fruits recording the highest value. Lagerstroemia speciosa leaves exhibited the highest IVDMD (65.91%) and IVOMD (62.84%), whereas Areca catechu sheath recorded the lowest values (42.38 and 39.85%, respectively). Crude fibre was negatively associated with digestibility ($r = -0.72$, $P < 0.001$), whereas CP showed a positive association ($r = 0.45$, $P < 0.05$). Flavonoid concentration was also negatively associated with digestibility ($r = -0.66$). The findings demonstrate considerable variation in the nutritional and phytochemical profiles of indigenous browse resources. L. speciosa leaves and G. arborea fruits emerged as promising resources based on their digestibility and protein concentration, respectively. These findings provide baseline information for selecting locally available browse materials for further nutritional evaluation and the development of locally adapted goat-feeding strategies.

Keywords: Assam Hill goat; Browse resources; Feed quality; Phytochemicals; In vitro digestibility; Tropical feeding systems

Introduction

Small ruminant production contributes substantially to rural livelihoods, household nutrition and income generation, particularly among resource-limited farming communities in developing countries. Goats are valued for their adaptability to diverse agroecological conditions, ability to utilize a wide range of vegetation and relatively low investment requirements. However, productivity in smallholder goat production systems is frequently constrained by seasonal fluctuations in feed availability, inadequate nutrient supply and limited access to affordable conventional feed ingredients. Identification and nutritional evaluation of locally available feed resources are therefore important for developing sustainable feeding strategies and reducing dependence on externally sourced feeds.

Goats are intermediate selective feeders with a preference for browse vegetation (Schwartz and Schafft, 1988). In tropical and subtropical regions, tree leaves, shrubs and other naturally occurring vegetation constitute important components of goat-feeding systems (Sahoo and Karim, 2010). These resources can provide protein, minerals and other nutrients, particularly during periods of pasture scarcity, and may complement grasses and agricultural residues. However, their nutritional value varies considerably with plant species, plant part, maturity, growing conditions and environmental factors (Le Houérou, 1980). In addition, structural fibre and plant secondary metabolites, including tannins, saponins and other phenolic compounds, can influence nutrient availability, feed utilization and ruminal fermentation (Besharati et al., 2022). Consequently, the nutritional evaluation of browse resources requires consideration of both their chemical composition and digestibility.

The importance of locally available feed resources is particularly relevant in Northeast India, where diverse vegetation and traditional livestock-management practices support indigenous goat production. Assam Hill goat (AHG), an indigenous goat population of Assam, is predominantly maintained under extensive and semi-intensive production systems, in which grazing and browsing are important feeding practices. Goats utilize naturally available grasses, shrubs, tree foliage and agricultural residues, reflecting the close association between local vegetation and traditional livestock production (Doley et al., 2023). Nevertheless, the nutritional contribution of individual browse species remains insufficiently characterized, limiting their systematic incorporation into balanced feeding strategies. Reliable information on the nutritive value of these resources could facilitate their appropriate utilization in locally adapted feeding systems.

Previous studies have investigated the chemical composition and feeding potential of different browse species and tree foliage (Norton, 1998; Lamidi et al., 2009; Nayak et al., 2012; Augustine et al., 2018; Aruwayo and Adeleke, 2019). Plant secondary metabolites may also influence ruminal fermentation and nutrient utilization, although their effects depend on compound type, concentration and dietary context (Devendra, 1990; Ebrahim and Negussie, 2020; Tedeschi et al., 2021). Tannins, for example, can interact with dietary proteins and modify their degradation and utilization by ruminants (Makkar, 2003; Patra and Saxena, 2011). However, the presence of bioactive compounds alone does not establish their beneficial or adverse effects on animal health

and productivity. Their nutritional significance must be interpreted alongside the chemical composition and digestibility of the feed material.

Chemical analysis provides information on the nutrient composition of feed resources, whereas in vitro digestibility measurements offer complementary information on the susceptibility of feed components to microbial and enzymatic degradation (Tilley and Terry, 1963). These methods are useful for comparing alternative feed resources and identifying promising materials for subsequent feeding trials. Previous studies have demonstrated the potential of browse foliage in small-ruminant nutrition, including its use as a component of alternative feeding systems (Salem et al., 2005; Bakshi and Wadhwa, 2007). Nevertheless, information on the nutritional composition, phytochemical characteristics and digestibility of indigenous browse resources available to Assam Hill goats remains limited.

Therefore, the present study was undertaken to evaluate the proximate composition, fibre fractions, mineral content, selected secondary metabolites and in vitro digestibility of eight indigenous browse resources available in the Eastern Brahmaputra Valley of Assam. The study aimed to characterize their nutritional variability and identify promising resources for further evaluation in Assam Hill goat-feeding systems.

Materials and methods

Study area and sampling design

The study was conducted in five districts of the Eastern Brahmaputra Valley of Assam, India (Table 1).

Table 1. Geographical and climatic profile of the selected study districts

Districts	Geographic location	Average rainfall	Temperature (°C)	Geographical area
Dhemaji	27°15'N and 27°55'N latitudes and 94°10'E and 95°30'E longitudes	300 cm	7-31	3237 square km
North Lakhimpur	26°45'N and 27°35'N latitudes and 93°40'E and 94°53'E longitudes	300 cm	7-31	2277 square km
Dibrugarh	27°10'N and 27°45'N latitudes and 94°30'E and 95°30'E longitudes	2134 mm	7-35	3381 square km
Sivsagar	26°42'N and 27°15' N latitude and 94°24'E and 95°23'E longitude.	2244.5 mm	6.9-37.2	2668 square km
Majuli	94°12'18"E and 95°41' 32" E longitudes and 27°05'27"N and 27°57' 16" N latitudes	3000 mm	8-35	352 square km

Collection and preparation of indigenous browse resources

Indigenous browse resources consumed by Assam Hill goats were identified through field observations and farmer interviews in five districts of the Eastern Brahmaputra Valley of Assam,

India. Eight browse resources were selected for nutritional and phytochemical evaluation (Fig. 1). Edible plant materials were collected from healthy, mature plants during the post-monsoon season (October-December), representing the period when these resources were available to goats. Approximately 500 g of edible material was collected from each plant. Samples of the same browse resource collected across the five districts were pooled to obtain one composite sample for each resource. The samples were transported to the laboratory, manually cleaned to remove soil, dirt and other extraneous materials, and oven-dried at 60°C overnight. The dried materials were ground to pass through a 1-mm sieve and stored in airtight containers until further analysis

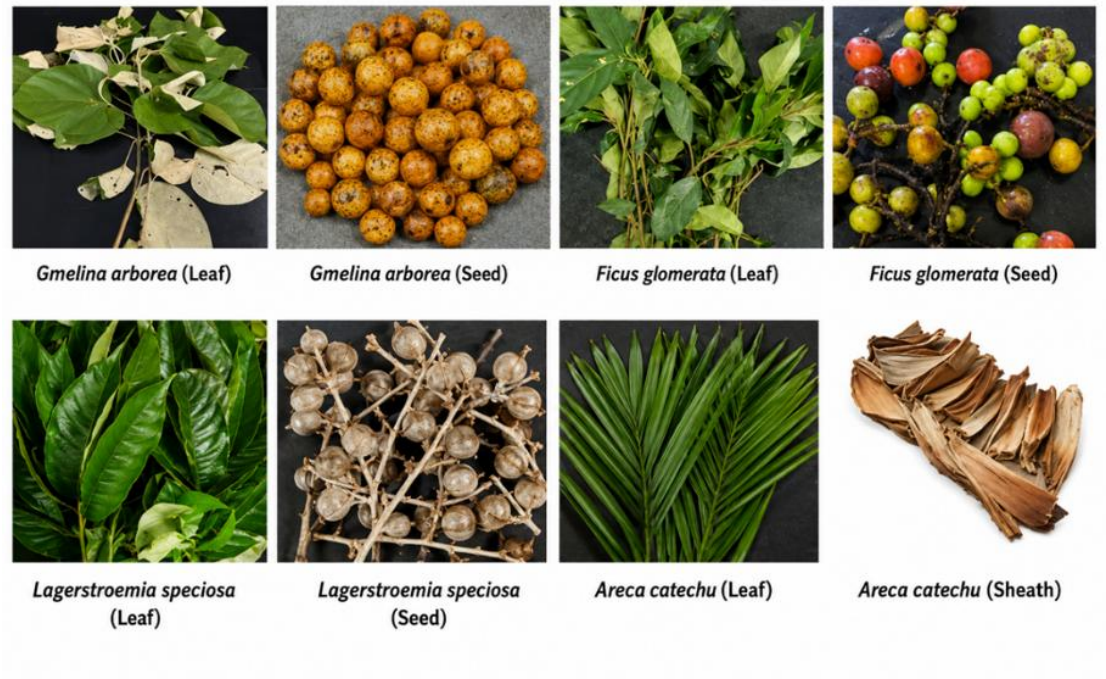


Fig. 1: Photographic documentation of indigenous browse species collected for nutritional and phytochemical analysis

For each feed resource, edible plant material was collected from the healthy and mature plants in each district from the portions normally browsed or consumed by goats. Approximately 500 g of edible material was collected from each plant. Samples obtained from the plants were pooled to prepare a composite sample for each feed resource within a district. The collected samples were transported to the laboratory, cleaned manually to remove soil, dirt and extraneous material and oven-dried at 60°C overnight. The dried material was ground to a fine powder and stored in airtight containers until analysis.

Analysis of collected feed resources

The proximate composition of the feed resources was determined in triplicate following the procedures of the Association of Official Analytical Chemists (AOAC, 2012). Neutral detergent fibre (NDF) and acid detergent fibre (ADF) were estimated according to the procedure described

by Van Soest et al. (1991). Calcium and phosphorus concentrations were determined following the modified procedure of Talapatra et al. (1940). Results were expressed on a dry matter basis (DMB).

Determination of secondary metabolites and minerals

Selected anti-nutritional factors and bioactive compounds were quantified using standard analytical procedures. Total tannins were determined using the Folin-Denis spectrophotometric method and expressed as tannic acid equivalents (TAE). Phytate was determined using the Wade reagent method. Saponins were quantified using gravimetric extraction with aqueous ethanol followed by n-butanol partitioning and subsequent vanillin-sulphuric acid colorimetric estimation. Oxalate was estimated by the potassium permanganate ($KMnO_4$) titrimetric method following acid extraction.

Total flavonoid content (TFC) was determined using the aluminium chloride colorimetric method, with absorbance measured at 415 nm and quercetin used as the reference standard. Results were expressed as quercetin equivalents (QE). All analyses were performed using analytical replicates, and the results were expressed as mean ± standard error (SE).

in vitro digestibility

in vitro dry matter digestibility

in vitro dry matter digestibility (IVDMD) was determined using the two-stage digestion procedure of Tilley and Terry (1963). Approximately 0.5 g of dried and ground feed sample was weighed into incubation tubes and incubated in triplicate with buffered rumen liquor obtained from healthy adult Assam Hill Goats using a stomach tube. The samples were incubated under anaerobic conditions at 39°C for 48 h. Following the first-stage fermentation, the residues were subjected to acid-pepsin digestion for a further 48 h. The remaining undigested residues were recovered by filtration, dried to constant weight and weighed. IVDMD was calculated as the proportion of dry matter lost during the two-stage digestion process and expressed as a percentage of the initial dry matter.

$$IVDMD(\%) = \frac{Initial\ dry\ matter - Residual\ dry\ matter}{Initial\ dry\ matter} \times 100$$

in vitro organic matter digestibility

in vitro organic matter digestibility (IVOMD) was calculated from the organic matter content of the feed sample and the corresponding undigested residue obtained after the two-stage digestion procedure. The results were expressed as percentage organic matter digestibility.

Statistical analysis

All statistical analyses were performed using Python version 3.12 with the pandas, SciPy, scikit-learn, statsmodels, Matplotlib and seaborn libraries. The analysis aimed to characterize variation

among locally available feed resources and identify nutritional and phytochemical factors associated with *in vitro* digestibility. The analytical workflow comprised descriptive and comparative analysis → Pearson correlation and heatmap → PCA → HCA → multiple linear regression → stepwise regression. For feed-resource analyses, laboratory replicates were used as analytical observations. Statistical significance was considered at $P < 0.05$.

Pearson correlation and heatmap

Pearson's product-moment correlation was used to assess the direction and strength of linear associations among nutritional composition, fibre fractions, minerals, secondary metabolites and *in vitro* digestibility parameters (Schober et al., 2018). Correlations were calculated using the replicate-level feed-resource data (n = 24) for IVDMD and IVOMD. Two-tailed tests were used, with $P < 0.05$ considered significant. The correlation matrix was visualized as a heatmap to facilitate interpretation of positive and negative associations. Correlations were interpreted as statistical associations rather than causal relationships.

Principal Component Analysis (PCA)

PCA was performed to reduce dimensionality and identify the major nutritional gradients differentiating the feed resources (Jolliffe & Cadima, 2016). PCA was conducted on species/plant-part mean data (n = 8) using 14 variables: ash, CP, CF, EE, NFE, NDF, ADF, tannin, oxalate, phytate, saponin, flavonoid, Ca and P. Variables were z-score standardized before analysis. Components were retained using the Kaiser criterion (eigenvalue > 1) and scree-plot assessment. Eigenvalues, percentage variance and cumulative variance were calculated and component loadings were used to identify variables contributing most strongly to each component. A PC1-PC2 biplot was generated for visual interpretation of feed-resource patterns.

Hierarchical Cluster Analysis (HCA)

Agglomerative HCA was performed to classify feed resources according to their overall nutritional similarity (Ward, 1963). The analysis used the same standardized variables as PCA, with Euclidean distance and Ward's minimum-variance method. The resulting relationships were presented as a dendrogram. Thus, PCA identified the major nutritional gradients, whereas HCA identified groups of feed resources with similar multivariate profiles.

Multiple and stepwise regression

Multiple linear regression was used to assess the combined associations of nutritional and phytochemical variables with IVDMD and IVOMD, analyzed separately. The predictors included CP, CF, EE, NFE, NDF, ADF, tannin, oxalate, phytate, saponin, flavonoid, Ca, P and ash. The full model was fitted using the Enter method and model performance was evaluated using R^2, adjusted R^2, F-statistic, regression coefficients, standard errors and P-values.

Stepwise regression was subsequently used to identify a more parsimonious set of predictors using the replicate-level dataset (n = 24). Variables were entered at $P < 0.05$ and removed at $P > 0.10$.

Separate models were developed for IVDMD and IVOMD. The final models were evaluated using R^2, adjusted R^2, F-statistic, coefficients and P-values. Because stepwise selection is data-driven and can be affected by correlated predictors and model-selection bias, the resulting models were interpreted as exploratory associations rather than definitive causal relationships.

3. Results

Chemical composition and fibre fractions of indigenous browse resources

The proximate composition and fibre fractions of the eight indigenous browse resources varied considerably among species and plant parts (Table 2). Crude protein (CP) concentration ranged from 3.53% in Areca catechu sheath to 21.50% in Gmelina arborea fruits. Relatively high CP concentrations were also observed in Lagerstroemia speciosa fruits (18.03%), G. arborea leaves (14.68%) and Ficus glomerata fruits (14.40%). In comparison, A. catechu sheath had the lowest CP concentration, indicating its limited contribution as a protein source.

Crude fibre (CF) concentration ranged from 8.50% in F. glomerata fruits to 33.70% in A. catechu sheath. Neutral detergent fibre (NDF) varied from 39.18% in L. speciosa fruits to 68.22% in A. catechu leaves, while acid detergent fibre (ADF) ranged from 24.16% in G. arborea fruits to 52.51% in A. catechu leaves. Ether extract (EE) was highest in G. arborea fruits (9.26%) and lowest in A. catechu sheath (0.07%). Nitrogen-free extract (NFE) ranged from 50.64% in G. arborea fruits to 70.93% in F. glomerata leaves. Overall, the results indicated considerable variation in protein, fibre and other proximate constituents among the evaluated browse materials.

Table 2. Chemical composition and fibre fractions of locally available feed resources (%DMB)

Feedstuff	*G. arborea* (Leaves)	*G. arborea* (Fruits)	*F. glomerata* (Leaves)	*F. glomerata* (Fruits)	*L. speciosa* (Leaves)	*L. speciosa* (Fruits)	*A. catechu* (Leaves)	*A. catechu* (Sheath)
Chemical composition (%)								
Organic matter	93.75±0.29	92.60±0.17	93.16±0.09	91.75±0.14	93.91±0.14	91.57±0.12	90.79±0.15	93.60±0.21
Total ash	6.25±0.20	7.40±0.12	6.85±0.06	8.25±0.10	6.09±0.10	8.43±0.09	9.21±0.10	6.40±0.15
Acid soluble ash	1.27±0.73	6.03±0.33	4.95±0.13	6.53±0.36	4.24±0.18	6.52±0.06	7.51±0.29	4.65±0.11
AIA	1.92±0.45	1.37±0.16	1.89±0.08	1.72±0.26	1.85±0.22	1.91±0.18	1.70±0.20	1.75±0.15
CP	14.68±0.22	21.50±0.67	7.20±0.14	14.40±0.24	12.48±0.15	18.03±0.07	11.60±0.28	3.53±0.11
CF	16.45±0.26	11.20±0.14	12.60±0.35	8.50±0.48	20.73±0.38	17.50±0.31	21.54±0.21	33.70±0.04
EE	4.50±0.37	9.26±0.14	2.42±0.05	3.15±0.05	2.34±0.05	3.84±0.05	2.00±0.23	0.07±1.33
NFE	58.12±0.28	50.64±0.33	70.93±0.89	65.70±0.33	58.36±0.17	52.20±0.59	55.65±0.33	56.30±0.39
Total CHO	74.56±0.77	61.84±0.57	83.53±1.32	74.20±0.23	79.09±0.77	69.70±1.27	77.19±0.76	59.83±0.62
Minerals (%)								
Ca	1.82±0.06	0.68±0.03	1.74±0.04	0.82±0.02	1.62±0.05	0.86±0.03	1.42±0.03	0.84±0.03

P	0.24±0.03	0.30±0.04	0.21±0.02	0.32±0.02	0.18±0.02	0.24±0.02	0.21±0.02	0.16±0.03
Fibre fractions (%)								
NDF	64.70±0.79	55.12±0.09	51.28±0.27	42.36±0.19	55.72±0.34	39.18±0.09	68.22±0.44	46.60±0.25
ADF	31.28±0.52	24.16±0.09	35.47±0.25	28.14±0.10	42.35±0.17	28.64±0.28	52.51±0.30	34.62±0.64
ADL	7.00±0.33	6.75±0.28	6.69±0.35	6.69±0.36	6.60±0.23	6.64±0.20	6.46±0.67	6.21±0.30
Cellulose	24.28±1.06	17.41±0.25	28.78±0.61	21.44±0.49	35.75±0.22	22.00±0.39	22.18±0.46	28.41±1.46
Hemicellulose	33.42±0.50	30.96±0.16	15.81±0.13	14.22±0.20	13.37±0.24	10.54±0.27	10.54±0.27	11.98±0.57

206

207 3.2 Plant secondary metabolites and mineral composition

208 The concentrations of secondary metabolites and mineral constituents also varied markedly among
209 feed resources and plant parts (Table 3). Total tannin concentration ranged from 1.43 to 6.45 mg
210 TAE/g, with the highest value in *L. speciosa* fruits and the lowest in *G. arborea* leaves. Oxalate
211 ranged from 0.24% in *F. glomerata* leaves to 6.70% in *G. arborea* fruits, while phytate ranged
212 from 0.29 to 5.68%, with both reaching their highest values in *G. arborea* fruits. These compounds
213 can influence mineral availability, although their effects in ruminants depend on dietary
214 concentration and ruminal degradation or transformation. Saponin ranged from 0.75% in *G.*
215 *arborea* leaves to 3.94% in *G. arborea* fruits.

216 **Table 3: Plant secondary metabolites (DMB)**

Feedstuff	*G. arborea* (Leaves)	*G. arborea* (Fruits)	*F. glomerata* (Leaves)	*F. glomerata* (Fruits)	*L. speciosa* (Leaves)	*L. speciosa* (Fruits)	*A. catechu* (Leaves)	*A. catechu* (Sheath)
Tannin (mg TAE/g)	1.43±0.03	3.16±0.04	2.15±0.06	4.22±0.03	3.12±0.02	6.45±0.22	4.65±0.10	3.12±0.04
Oxalate (%)	1.80±0.05	6.70±0.11	0.24±0.02	0.38±0.01	1.24±0.02	0.68±0.02	1.22±0.06	1.65±0.03
Phytate (%)	0.95±0.02	5.68±0.14	0.29±0.01	0.46±0.02	0.87±0.01	1.05±0.02	1.35±0.10	0.95±0.03
Saponin (%)	0.75±0.03	3.94±0.07	1.12±0.01	1.85±0.22	1.24±0.02	1.62±0.01	2.35±0.10	1.45±0.10
Flavonoid (mg QE/g)	3.21±0.08	5.80±0.10	6.80±0.10	9.60±0.12	10.60±0.06	14.82±0.18	26.50±0.29	17.88±0.25

217 Total flavonoid concentration varied from 3.21 mg QE/g in *G. arborea* leaves to 26.50 mg QE/g
218 in *A. catechu* leaves. The high flavonoid concentration in *A. catechu* leaves indicates a
219 comparatively rich flavonoid profile, although total flavonoid concentration alone cannot establish
220 a specific biological effect. Calcium ranged from 0.68% in *G. arborea* fruits to 1.82% in *G.*
221 *arborea* leaves, while phosphorus ranged from 0.16% in *A. catechu* sheath to 0.32% in *F.*
222 *glomerata* fruits. The variation in Ca and P highlights the importance of mineral balance when
223 these materials are incorporated into complete goat diets.

224 *3.3 in vitro digestibility of locally available feed resources*

225 The *in vitro* digestibility measurements revealed substantial differences among species and plant
226 parts (Table 4). IVDMD ranged from 42.38% in *A. catechu* sheath to 65.91% in *L. speciosa* leaves,

while IVOMD ranged from 39.85 to 62.84%, respectively. Thus, *L. speciosa* leaves exhibited the highest IVDMD and IVOMD, whereas *A. catechu* sheath recorded the lowest values. *G. arborea* leaves showed IVDMD and IVOMD values of 62.40 and 58.70%, respectively, compared with 61.42 and 58.76% for its fruits. *F. glomerata* leaves exhibited greater digestibility than its fruits (63.75 versus 59.63% IVDMD; 60.48 versus 56.92% IVOMD). Similarly, *L. speciosa* leaves were more digestible than its fruits (65.91 versus 60.27% IVDMD; 62.84 versus 57.35% IVOMD). *A. catechu* showed markedly lower digestibility, particularly for the sheath.

Table 4: ***in vitro*** **dry matter and organic matter digestibility**

Feedstuff	*G. arborea* (Leaves)	*G. arborea* (Fruits)	*F. glomerata* (Leaves)	*F. glomerata* (Fruits)	*L. speciosa* (Leaves)	*L. speciosa* (Fruits)	*A. catechu* (Leaves)	*A. catechu* (Sheath)
IVDMD(%)	62.40±0.28	61.42±0.92	63.75±1.52	59.63±1.52	65.91±0.48	60.27±0.99	48.56±0.82	42.38±0.41
IVOMD(%)	58.70±0.52	58.76±0.76	60.48±0.95	56.92±0.95	62.84±1.13	57.35±0.56	45.62±1.88	39.85±0.39

The overall nutritional profiles of the eight browse resources are illustrated by the normalized radar plot (Fig. 2). The distinct profiles demonstrate considerable variation among species and plant parts. *L. speciosa* leaves showed a comparatively favourable combination of nutrient and digestibility characteristics, whereas *A. catechu* sheath exhibited a contrasting profile associated with relatively high fibre and lower digestibility. The observed variation further supports the use of an integrated assessment of nutrients, fibre fractions, minerals, secondary metabolites and digestibility for evaluating the feeding potential of indigenous browse resources.

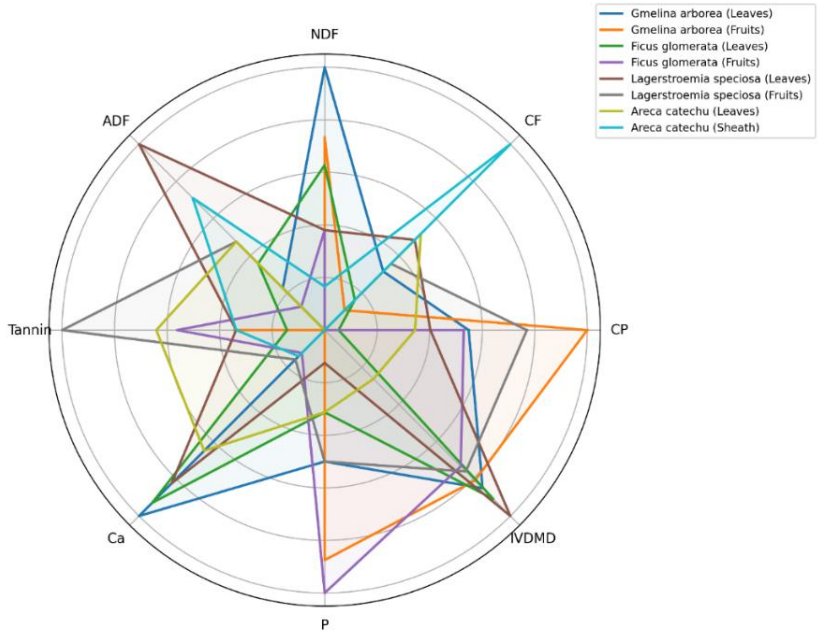


Fig. 2: Radar plot showing normalized nutritional, fibre, mineral, secondary-metabolite and digestibility characteristics of the evaluated indigenous browse resources

3.4 Correlation between nutritional characteristics and digestibility

Pearson correlation analysis revealed several significant associations among nutritional composition, fibre fractions, minerals, secondary metabolites and digestibility parameters (Fig. 3). IVDMD and IVOMD were very strongly correlated ($r = 0.99$, $P < 0.001$), indicating that the two digestibility measures provided highly consistent ranking of the evaluated browse resources. Crude fibre exhibited the strongest negative association with both IVDMD and IVOMD ($r = -0.72$, $P < 0.001$ for both), suggesting that resources with higher crude fibre tended to exhibit lower digestibility. Similarly, total flavonoid concentration was negatively correlated with IVDMD ($r = -0.66$, $P < 0.001$) and IVOMD ($r = -0.66$, $P = 0.001$). In contrast, CP showed significant positive associations with IVDMD ($r = 0.45$, $P = 0.029$) and IVOMD ($r = 0.45$, $P = 0.026$).

NDF showed significant positive correlations with IVDMD ($r = 0.56$, $P = 0.005$) and IVOMD ($r = 0.54$, $P = 0.006$). Although this relationship appears counterintuitive because NDF represents a structural fibre fraction, it should be interpreted cautiously as a species and plant part-specific association rather than evidence that increasing NDF enhances digestibility. The observed positive correlation may reflect the particular combination of nutritional characteristics among the eight browse resources and should not be interpreted causally.

Phosphorus showed positive but non-significant associations with IVDMD ($r = 0.38$, $P = 0.066$) and IVOMD ($r = 0.40$, $P = 0.051$), while calcium showed similarly non-significant positive associations with IVDMD ($r = 0.36$, $P = 0.083$) and IVOMD ($r = 0.33$, $P = 0.116$). Tannin, ADF, EE, saponin, phytate, oxalate, ash and NFE were not significantly correlated with either digestibility measure ($P > 0.05$).

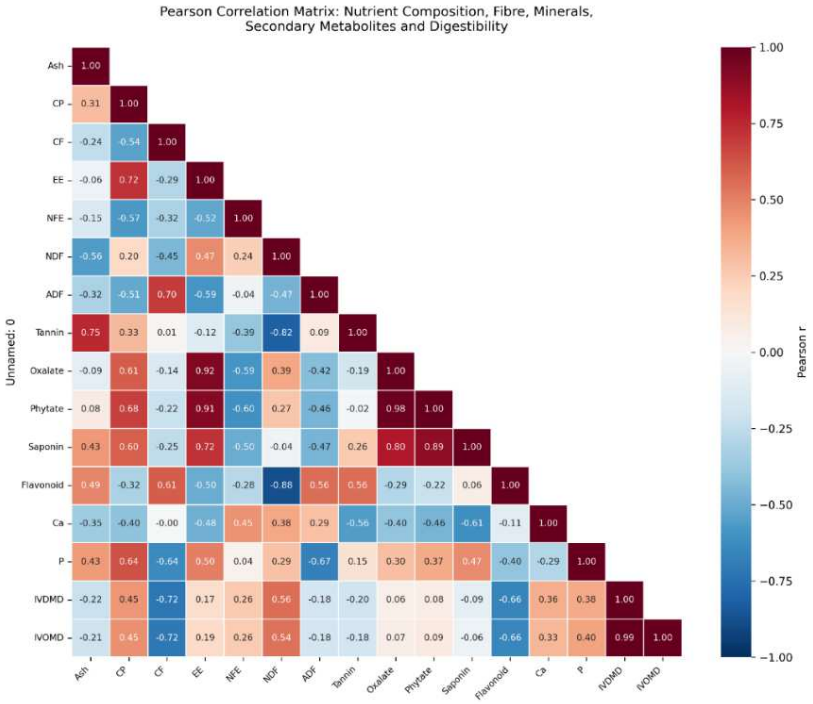


Fig. 3: Pearson correlation heatmap showing relationships among proximate composition, fibre fractions, minerals, secondary metabolites and in vitro digestibility parameters of the evaluated feed resources

3.5 Principal Component Analysis

Principal Component Analysis (PCA) was performed on standardized (z-scored) species-mean values of 14 nutritional variables: ash, CP, CF, EE, NFE, NDF, ADF, tannin, oxalate, phytate, saponin, flavonoid, Ca and P. The analysis included the eight evaluated feed resources. Three components had eigenvalues >1 and were therefore retained according to the Kaiser criterion. Collectively, PC1, PC2 and PC3 explained 87.59% of the total variance (Table 5), indicating that most of the nutritional variability among the browse resources could be summarized by three major dimensions.

Table 5. Eigenvalues and percentage variance explained by the principal components

PC	Eigenvalue	% Variance	Cumulative %
1	6.996	43.73	43.73
2	4.354	27.21	70.94
3	2.665	16.66	87.59
4	0.806	5.03	92.63
5	0.706	4.41	97.04
6	0.359	2.24	99.29
7	0.114	0.71	100.00

PC1 had an eigenvalue of 6.996 and accounted for 43.73% of the total variance. Strong positive loadings were observed for EE (0.989), phytate (0.950), CP (0.907), oxalate (0.903), saponin (0.880) and P (0.832), whereas ADF (−0.802), CF (−0.589), Ca (−0.582) and NFE (−0.491) showed negative loadings (Table 6). Thus, PC1 primarily represented a nutrient-phytochemical gradient, contrasting variables associated with CP, EE, minerals and secondary metabolites with structural fibre and NFE.

Table 6. Loadings of nutritional variables on the first three principal components

Variable	PC1	PC2	PC3
CP	0.907	-0.153	-0.112
EE	0.989	0.119	0.347
Oxalate	0.903	0.032	0.543
Phytate	0.950	-0.102	0.416
Saponin	0.880	-0.407	0.125
P	0.832	0.106	-0.619
ADF	-0.802	-0.278	0.472
Ca	-0.582	0.616	0.009

NDF	0.394	0.976	0.115
Tannin	0.075	-0.939	-0.386
Flavonoid	-0.472	-0.880	0.117
Ash	0.240	-0.740	-0.637
CF	-0.589	-0.400	0.727
NFE	-0.491	0.597	-0.575

PC2 had an eigenvalue of 4.354 and explained 27.21% of the total variance. NDF showed the strongest positive loading (0.976), followed by Ca (0.616) and NFE (0.597), whereas tannin (−0.939), flavonoid (−0.880) and ash (−0.740) showed strong negative loadings. PC2 therefore represented a structural-fibre/mineral versus secondary-metabolite gradient.

PC3 had an eigenvalue of 2.665 and contributed 16.66% of the total variance. CF (0.727), oxalate (0.543) and ADF (0.472) loaded positively, whereas ash (−0.637), P (−0.619) and NFE (−0.575) loaded negatively. The PC1–PC2 biplot (Fig. 4) consequently demonstrates that the browse resources were differentiated by a combination of primary nutrients, fibre fractions, minerals and secondary metabolites, rather than by a single nutritional characteristic.

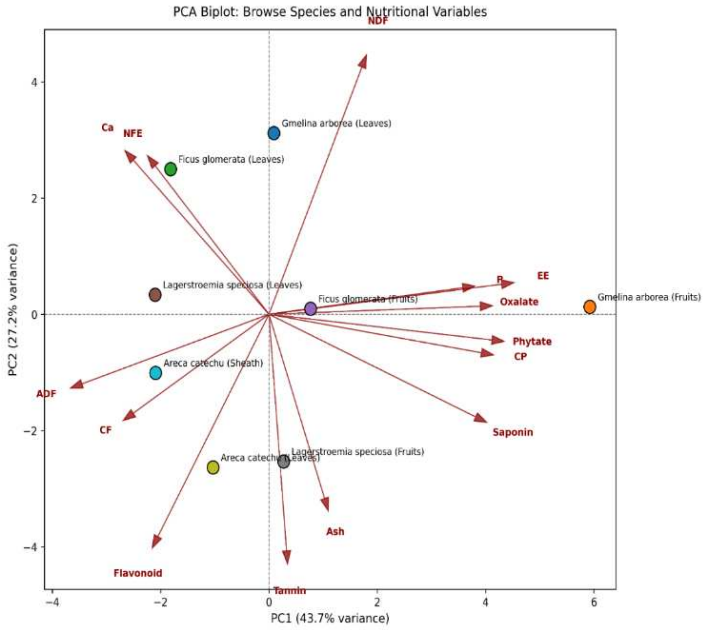


Fig. 4: PCA biplot (PC1 vs PC2) of nutritional variables

The PCA findings complement the correlation analysis by demonstrating that several nutritional and phytochemical variables contributed simultaneously to the overall differentiation of browse resources. This multidimensional pattern supports the use of integrated nutritional profiling when selecting indigenous browse resources for incorporation into Assam Hill Goat feeding systems.

3.6 Hierarchical Cluster Analysis

Agglomerative hierarchical cluster analysis (HCA) using Ward's minimum variance method and Euclidean distance on standardized variables was performed to further classify the browse resources according to similarities in their overall nutritional profiles. The resulting dendrogram (Fig. 5) demonstrated distinct patterns of similarity among the evaluated resources. The reported three-cluster solution is presented in Table 7.

Table 7. Cluster membership based on standardized nutritional composition.

Cluster	Feed resources
Cluster I	*F. glomerata*; *L. speciosa*; *A. catechu*
Cluster II	*G. arborea*; *F. glomerata*; *L. speciosa*; *A. catechu*
Cluster III	*G. arborea*

The clustering pattern indicates that nutritional similarity was not determined exclusively by botanical identity and may also reflect differences associated with plant part and its corresponding chemical composition. This is consistent with the PCA results, which demonstrated substantial variation in the nutritional and phytochemical characteristics of the evaluated resources.

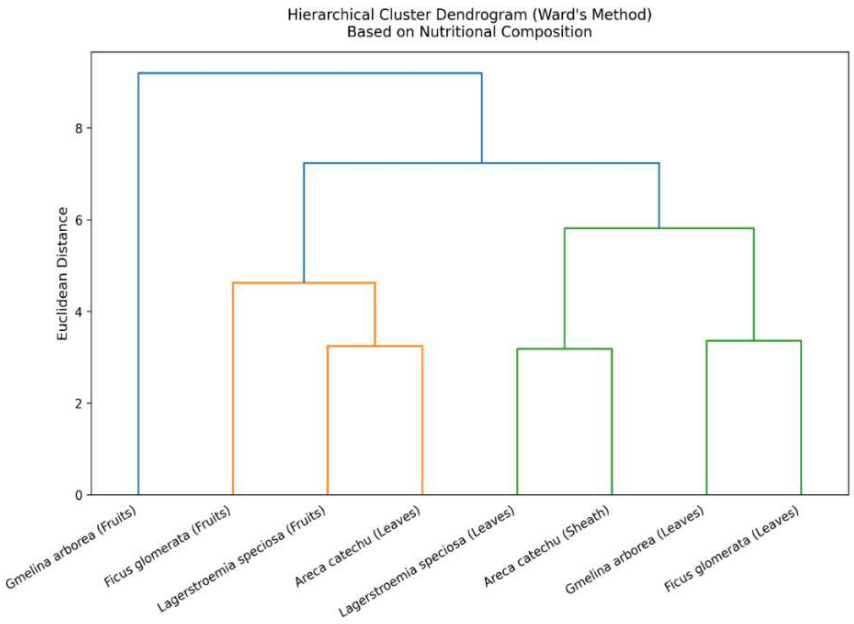


Fig. 5: Dendrogram showing hierarchical clustering of browse species based on nutritional composition

Overall, PCA and HCA provide complementary evidence that the evaluated browse resources occupy distinct nutritional profiles, with variation driven by the combined effects of nutrient composition, fibre fractions, minerals and phytochemicals. These findings support the subsequent regression analyses to identify the specific nutritional variables most strongly associated with IVDMD and IVOMD.

3.7 Multiple regression analysis of IVDMD

Multiple linear regression was used to identify nutritional and phytochemical variables associated with IVDMD. The full model was highly significant ($R^2 = 0.996$, adjusted $R^2 = 0.989$; $F(14,9) = 150.7$, $P < 0.001$) and explained 99.6% of the observed variation. Significant individual predictors were CP, NDF, ADF, saponin, flavonoid and Ca. CP showed a positive coefficient ($\beta = 1.335$, $P = 0.003$), NDF a negative coefficient ($\beta = -0.768$, $P = 0.012$), ADF a positive adjusted coefficient ($\beta = 0.254$, $P = 0.048$), saponin a positive coefficient ($\beta = 7.042$, $P = 0.014$), flavonoid a negative coefficient ($\beta = -1.231$, $P = 0.001$), and Ca a positive coefficient ($\beta = 17.104$, $P = 0.001$).

The full equation was: IVDMD = 44.461 + 1.335(CP) − 0.247(CF) + 0.649(EE) + 0.437(NFE) − 0.768(NDF) + 0.254(ADF) + 0.278(Tannin) + 3.118(Oxalate) − 6.189(Phytate) + 7.042(Saponin) − 1.231(Flavonoid) + 17.104(Ca) − 0.478(P) − 2.660(Ash).

The very high R^2 should be interpreted cautiously because 14 predictors were fitted using only 24 observations. Intercorrelations among nutritional variables may produce multicollinearity and overfitting; consequently, the full model is best regarded as exploratory rather than as a validated predictive model.

3.8 Multiple regression analysis of IVOMD

The corresponding full model for IVOMD was also highly significant ($R^2 = 0.987$, adjusted $R^2 = 0.968$; $F(14,9) = 50.7$, $P < 0.001$), explaining 98.7% of the observed variation. The consistency of the high explanatory capacity of the IVDMD and IVOMD models indicates that the measured nutritional and phytochemical variables collectively captured much of the variation in digestibility.

Stepwise regression analysis of IVDMD

Because the full model included many predictors relative to the sample size, stepwise regression was used to identify a more parsimonious set of variables. Using entry $P < 0.05$ and removal $P > 0.10$, five variables CF, ADF, flavonoid, CP and Ca were retained. The final model was highly significant ($R^2 = 0.965$, adjusted $R^2 = 0.956$; $F(5,18) = 100.5$, $P < 0.001$), explaining 96.5% of the variation in IVDMD.

CF showed a strong negative coefficient ($\beta = -0.775$, $P < 0.001$), flavonoid was also negative ($\beta = -0.507$, $P < 0.001$), whereas CP ($\beta = 0.573$, $P < 0.001$) and Ca ($\beta = 4.182$, $P < 0.001$) were positive. ADF showed a positive adjusted coefficient ($\beta = 0.578$, $P < 0.001$). Importantly, this ADF coefficient should not be interpreted as evidence that increasing ADF improves digestibility because its simple correlation with IVDMD was weak and non-significant ($r = -0.18$, $P = 0.399$). The adjusted coefficient likely reflects shared variance among correlated fibre predictors.

The final equation was: IVDMD = 43.721 − 0.775(CF) + 0.578(ADF) − 0.507(Flavonoid) + 0.573(CP) + 4.182(Ca).

Stepwise regression analysis of IVOMD

The stepwise IVOMD model retained the same five variables—CF, ADF, flavonoid, CP and Ca. The model was highly significant ($R^2 = 0.941$, adjusted $R^2 = 0.924$; $F(5,18) = 57.2$, $P < 0.001$) and explained 94.1% of the variation in IVOMD. CF ($\beta = -0.766$, $P < 0.001$) and flavonoid ($\beta = -0.498$, $P < 0.001$) were negative predictors, whereas CP ($\beta = 0.558$, $P < 0.001$) and Ca ($\beta = 3.482$, $P = 0.011$) were positive predictors. ADF again showed a positive adjusted coefficient ($\beta = 0.577$, $P < 0.001$), despite its weak negative bivariate correlation with IVOMD ($r = -0.18$, $P = 0.395$).

The final equation was: IVOMD = 41.570 − 0.766(CF) + 0.577(ADF) − 0.498(Flavonoid) + 0.558(CP) + 3.482(Ca). The identical predictor set retained for IVDMD and IVOMD indicates a consistent multivariable structure underlying the two digestibility measures.

3.9 Integrated interpretation of nutritional quality and digestibility

The integrated results demonstrate that the locally available feed resources used by Assam Hill Goats represent a heterogeneous group in terms of proximate composition, fibre fractions, minerals and secondary metabolites. The variation in CP, fibre, NFE, phytochemicals and minerals was accompanied by substantial differences in IVDMD and IVOMD. *L. speciosa* leaves recorded the highest digestibility, whereas *A. catechu* sheath recorded the lowest, indicating marked differences in potential feed utilization among plant parts.

The correlation, PCA, HCA and regression analyses provide convergent evidence that feed quality is multidimensional. CF and flavonoid concentration were consistently associated with lower digestibility, while CP was positively associated with digestibility. PCA further showed that three major nutritional dimensions accounted for 87.59% of total variation, with strong contributions from primary nutrients, fibre fractions, minerals and secondary metabolites. HCA independently demonstrated nutritional differentiation among the browse resources.

The positive adjusted ADF coefficients in the stepwise models should be interpreted cautiously because ADF is chemically related to CF and NDF. The contrast between the weak negative bivariate ADF digestibility relationship and its positive adjusted regression coefficient illustrates the influence of shared variance and multicollinearity. Therefore, the regression coefficients should be interpreted as statistical associations within the fitted models rather than as direct causal effects.

Taken together, the results support an integrated concept of browse-feed quality in which protein supply, structural fibre, mineral composition and secondary metabolites jointly determine the nutritional potential and digestibility of locally available resources. This multidimensional evidence provides a stronger basis for ranking feed resources than reliance on a single parameter such as CP, CF or digestibility. It also provides the statistical foundation for developing a Feed Quality Index (FQI) that can integrate favourable nutritional attributes with digestibility and potentially penalize undesirable phytochemical characteristics. Such an index could be particularly useful for identifying priority browse resources for low-input Assam Hill Goat production systems.

4. Discussion

The present study revealed considerable variation in the nutritional composition of 8 indigenous browse resources consumed by Assam Hill Goats (AHG), highlighting the importance of evaluating individual plant species and plant parts before their inclusion in feeding programmes. Most of the evaluated browse materials contained CP percentage above the approximate level generally considered necessary to support ruminal microbial activity, although their effective contribution to goat nutrition would also depend on intake, degradability and the presence of secondary metabolites (Van Soest, 1994). These findings support the potential role of indigenous tree foliage and fruits in supplementing conventional feed resources in smallholder goat production systems. The dry matter, crude protein and nitrogen-free extract contents of Gmelina fruits recorded in the present study were slightly higher than those reported by Amata (2012) for ripe Gmelina fruits. Such variations may be attributed to differences in geographical location, soil characteristics, climatic conditions and analytical procedures. Azor and Abimbola (2003) also reported that processed Gmelina fruits could be incorporated into animal diets without adverse effects. The crude protein content of the leaves observed in the present study falls within the range of 12-30% reported for most tropical tree species by Norton (1998). However, the crude protein and ether extract contents were comparatively lower than the values of 14.6% and 12.7%, respectively, reported by Amata and Lebari (2011). These variations may be associated with differences in geographical origin, soil fertility, climatic conditions, plant maturity and analytical methods. Bakshi and Wadhwa (2007) examined tree leaves as a complete feed for goat bucks, demonstrating the relevance of evaluating locally available foliage as an alternative feeding resource. Nevertheless, the variation observed in the present study indicates that browse materials should not be treated as nutritionally interchangeable. Rather, their incorporation into AHG diets should be guided by their nutrient composition, digestibility and the nutrient requirements of animals at different physiological stages.

The fibre fractions also differed markedly among the evaluated resources. These differences suggest that combining nutritionally complementary browse materials may be more useful than relying on a single species. However, the practical value of such combinations requires evaluation in balanced diets rather than being inferred solely from chemical composition. The high CF concentration of *A. catechu* sheath and high ADF concentration of *A. catechu* leaves indicate a substantial contribution of structural cell-wall components. Such components can influence microbial accessibility and feed utilization; however, the present dataset indicates that digestibility cannot be explained by a single fibre fraction alone

The browse resources differed substantially in their secondary metabolite concentrations, particularly tannins, oxalates, phytates, saponins and flavonoids. Total tannin concentration ranged from 1.43 mg tannic acid equivalents (TAE)/g in *G. arborea* leaves to 6.45 mg TAE/g in *L. speciosa* fruits. These differences are important because tannins can interact with dietary proteins and influence their degradation, ruminal fermentation and subsequent nutrient utilization (McSweeney et al., 2001; Min et al., 2003; Patra and Saxena, 2011). However, the effects of tannins depend on their chemical structure, concentration, dietary context and the ability of rumen

microorganisms to tolerate or metabolize them (Makkar, 2003; Patra and Saxena, 2011). Therefore, the presence of tannins should not automatically be interpreted as an adverse nutritional characteristic, nor should their potential benefits be assumed without further evaluation. Oxalate and phytate concentrations were particularly high in *G. arborea* fruits, at 6.70% and 5.68%, respectively. These compounds warrant attention because they may reduce the availability of certain minerals, depending on their concentrations, chemical forms and interactions with other dietary constituents. The comparatively high flavonoid concentration in *A. catechu* leaves (26.50 mg quercetin equivalents/g) and *A. catechu* sheath (17.88 mg quercetin equivalents/g) further demonstrates the diversity of phytochemical profiles among the evaluated resources. Although flavonoids and other plant secondary metabolites may influence ruminal microbial activity, their biological effects cannot be established from total concentrations alone. Further investigation of individual compounds, their bioavailability and their effects on rumen fermentation is needed before making specific nutritional or functional claims. Overall, the findings emphasize the need to consider both beneficial nutrients and potentially limiting constituents when evaluating indigenous browse materials for livestock feeding (Makkar, 2003; Patra and Saxena, 2011).

The mineral composition of the browse resources also varied, with calcium ranging from 0.68% in *G. arborea* fruits to 1.82% in *G. arborea* leaves, while phosphorus ranged from 0.16% in *A. catechu* sheath to 0.32% in *F. glomerata* fruits. These differences indicate that the contribution of browse materials to mineral nutrition may vary considerably among species and plant parts.

A major finding of the present study was the considerable variation in *in vitro* dry matter digestibility (IVDMD) and *in vitro* organic matter digestibility (IVOMD) among the eight browse resources. In the present study, the higher digestibility of *L. speciosa* leaves indicates their potential as a candidate browse ingredient for further nutritional evaluation. Similarly, the relatively high digestibility of *F. glomerata* and *G. arborea* leaves suggests that these resources may be useful components of locally adapted feeding systems. However, these laboratory estimates indicate potential digestibility rather than actual animal performance, voluntary intake or nutrient retention under farm conditions. The digestibility of leaves was higher than that of fruits for both *F. glomerata* and *L. speciosa*. This pattern demonstrates that plant part can be an important determinant of nutritional value, even within the same botanical species. Bakshi and Wadhwa (2007) also demonstrated differences in the feeding value of tree foliage and emphasized the importance of evaluating individual browse species rather than assuming that all tree leaves are equally suitable for livestock. The low digestibility of *A. catechu* sheath is consistent with its low CP concentration (3.53%), high CF concentration (33.70%) and very low ether extract (EE) concentration reported in the present study. These characteristics suggest comparatively limited nutrient density and digestibility. Nevertheless, its practical value should not be judged exclusively from laboratory digestibility; its potential role, if any, would need to be assessed within a complete diet containing adequate protein, energy and minerals. On the basis of the present findings, *L. speciosa* leaves appear particularly promising for further investigation, while *A. catechu* sheath

should not be considered a major nutrient-dense feed ingredient without appropriate supplementation and feeding evaluation.

The correlation analysis provided further insight into the nutritional factors associated with digestibility. Crude fibre showed a significant negative correlation with both IVDMD and IVOMD ($r=-0.72$, $P<0.001$), indicating that browse resources with higher CF tended to have lower digestibility. This relationship is consistent with the established role of structural plant components in determining the accessibility of nutrients to ruminal microorganisms (Van Soest, 1994). Crude protein exhibited a moderate positive correlation with IVDMD and IVOMD ($r=0.45$) for both, suggesting that protein-rich browse resources tended to be more digestible within the evaluated dataset. However, the relationship between fibre fractions and digestibility was not uniform. Although NDF showed a positive correlation with IVDMD ($r=0.56$, $P=0.005$)) and IVOMD ($r=0.54$, $P=0.006$), this result should not be interpreted as evidence that increasing NDF improves digestibility. Instead, it may reflect differences in the overall chemical composition of the selected species and plant parts. As fibre fractions coexist with other nutritional characteristics, their relationships with digestibility may vary across feed resources.

Flavonoid concentration was also negatively correlated with IVDMD and IVOMD ($r=-0.66$) for both). This association suggests that flavonoid-rich samples tended to have lower digestibility in the present dataset. Nevertheless, it does not establish that flavonoids directly inhibited digestion. Total flavonoid concentration does not distinguish among individual compounds, and the observed relationship may reflect differences in other characteristics associated with particular species or plant parts. The effects of plant secondary metabolites on ruminal fermentation are known to vary according to compound structure, concentration and dietary conditions (Patra and Saxena, 2011). The very strong correlation between IVDMD and IVOMD ($r=0.99$, $P<0.001$) indicates that the two parameters provided highly consistent rankings of the evaluated browse resources. Together, these findings suggest that digestibility was associated with a combination of protein concentration, fibre characteristics and phytochemical composition rather than any single nutritional component. As emphasized by Schober et al. (2018), correlations describe associations between variables and should not be interpreted as evidence of causation.

The principal component analysis (PCA) further demonstrated the multidimensional nature of browse-feed quality. The first three principal components accounted for 87.59% of the total variation in the 14 nutritional and phytochemical variables. PC1 explained 43.73% of the variance and was characterized by strong positive loadings for EE, phytate, CP, oxalate, saponin and phosphorus, while ADF, CF, calcium and NFE loaded negatively. PC2 explained 27.21% of the variance and primarily distinguished resources according to NDF, calcium and NFE in contrast to tannin, flavonoid and ash concentrations. These patterns indicate that differences among the browse resources involved several interacting nutritional dimensions. PCA is useful for reducing complex datasets to a smaller number of components while retaining much of their variation, thereby facilitating the interpretation of relationships among variables (Jolliffe and Cadima, 2016). In the present study, the PCA results complement the univariate and correlation analyses by

showing that the browse materials cannot be ranked reliably on the basis of CP or digestibility alone. Their nutritional profiles reflect the combined contributions of major nutrients, structural carbohydrates, minerals and secondary metabolites.

Hierarchical cluster analysis (HCA) similarly demonstrated differences in the overall nutritional profiles of the evaluated resources. The observed clustering patterns suggest that nutritional similarity was influenced by both botanical identity and plant part. This is relevant to practical feeding because leaves, fruits and other edible plant fractions from the same species may differ substantially in their chemical composition and digestibility. Nevertheless, PCA and HCA are exploratory tools, and the resulting groupings should be interpreted in the context of the relatively small number of evaluated feed resources.

The regression analyses identified CF, flavonoid concentration, CP and calcium among the variables associated with digestibility in the stepwise models. CF and flavonoids had negative coefficients, whereas CP and calcium had positive coefficients. ADF also had a positive adjusted coefficient despite its weak, non-significant negative bivariate correlation with digestibility. This apparent discrepancy may reflect shared variance among correlated predictors rather than a beneficial effect of ADF on digestion. Furthermore, the high R^2 values of the regression models should be interpreted cautiously because the models included multiple predictors relative to the limited number of analytical observations. These analyses therefore provide exploratory evidence of associations rather than validated prediction equations for animal performance.

5. Conclusion

The study demonstrated considerable variation in the nutritional composition, phytochemical characteristics and in vitro digestibility of indigenous browse resources consumed by Assam Hill Goats. *Lagerstroemia speciosa* leaves exhibited the highest digestibility, whereas *Gmelina arborea* fruits recorded the highest crude protein content. Crude fibre and flavonoid concentrations were negatively associated with digestibility, while crude protein showed a positive association. These findings identify promising browse resources for further nutritional evaluation and provide a basis for developing locally adapted feeding strategies. Further *in vivo* investigations are required to establish their dietary inclusion levels and effects on animal performance.

6. CRediT authorship contribution statement

Bornalee Handique: Writing - review & editing, Writing-original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. Da U Ruhi Pde: Writing - review & editing, Methodology, Investigation, Conceptualization. M. B. Chaudhary: Conceptualization, Investigation, Formal analysis. Lokesha E: review & editing, Methodology, Investigation, Chemical analysis. Dibyendu Deb: Review and editing, Data curation, Statstical analysis A. K. Balange: Writing - review & editing, supervision

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT Plus (OpenAI, San Francisco, CA, USA) to assist with improving the clarity and correctness of the English language in this manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare no conflict of interest

Data Availability declaration

Not applicable

Acknowledgements

The authors gratefully acknowledge the support of the Director, ICAR-Indian Agricultural Research Institute, Assam under the Indian Council of Agricultural Research (ICAR), Department of Agricultural Research and Education (DARE), Government of India.

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