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Research Article

Role of Soil Fertility in Influencing Nutritional Quality of Indigenous Browse Species in Mixed Crop–Livestock Systems

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Abstract

Indigenous browse species represent an underutilized feed resource for livestock in tropical systems; however, their nutritional quality and its relationship with soil fertility remain poorly understood, particularly in the Caribbean region. In Guyana, limited information exists on how soil conditions influence the nutritional composition of locally available browse species, constraining their effective utilization in livestock feeding systems. This study evaluated the nutritional quality of eleven indigenous browse species and examined their relationship with soil properties in the Linden area of region 10, Guyana. Leaf samples were analyzed for proximate composition and mineral content, while soil physicochemical characteristics at collection sites were also assessed. Significant interspecific variation ($p < 0.001$) was observed for all proximate parameters and for sodium and zinc among mineral parameters, while calcium and potassium showed no significant differences among species ($p > 0.05$). Crude protein ranged from 186,400 mg/kg (18.64%) in *Carica papaya* to 281,200 mg/kg (28.12%) in *Manihot esculenta*, while crude fibre varied widely, with the highest values recorded in *Pueraria montana*. Principal component analysis explained 44.86% of total variance, with the first principal component (PC1) accounting for 26.12%, highlighting clear separation among species based on their nutritional traits. Soils were slightly acidic (pH 5–6) with variable organic matter and nutrient availability, and soil physicochemical properties particularly pH, organic matter content, and cation exchange capacity were found to influence the mineral composition of browse foliage across collection sites. Among the species evaluated, *M. esculenta*, *Gliricidia sepium*, and *Ipomoea batatas* exhibited the highest crude protein concentrations, while *Colocasia esculenta* recorded the highest mineral content, supporting their potential as supplementary feed resources for livestock. These findings highlight the importance of soil–plant interactions in determining the feed quality of indigenous browse species and support their strategic use as sustainable supplementary feed resources in tropical livestock production systems.

Keywords: Browse Species, Nutritional Composition, Feed Supplementation, Soil Fertility, Sustainable Agriculture

1. Introduction

Livestock, particularly ruminants, play a multifaceted and indispensable role in smallholder farming systems across the developing world. Beyond providing direct products such as milk, meat, and skin, these animals contribute significantly to agricultural livelihoods through animal traction, manure for soil fertility enhancement, and as important sources of financial resilience during periods of economic or climatic uncertainty [1-5]. As global populations continue to expand and arable land becomes increasingly constrained, the pressure on agricultural systems to produce more food and forage intensifies [4]. This dynamic is especially relevant for regions with high dependence on smallholder livestock keeping, such as much of rural Guyana, where recent trends in the growing demand for animal-source foods have heightened the need for improved integration of smallholder farmers into livestock value chains to strengthen household food security and economic prospects [6].

A persistent challenge confronting smallholder livestock systems is insufficient access to high-quality feedstuffs that provide adequate energy and balanced amino acid profiles, nutritional attributes imperative for sustaining animal health and productivity [2, 7]. Soybean meal remains a globally prominent feed supplement due to its favourable energy density and protein quality; however, smallholders in Guyana and similar settings often encounter restricted access, as commercial entities dominate the market and prices continue to rise, placing additional strain on resource-limited producers. This recurring feed gap, which is particularly acute during the dry season, underscores the urgent need to identify and evaluate cost-effective, locally accessible alternative feed resources.

Among the most promising alternatives, indigenous

browse species, particularly leguminous trees and shrubs, stand out for their adaptability, ecological contributions, and nutritional potential. Browse species can persist and remain green during prolonged dry spells owing to their deep rooting systems, offering a critical feed supply when grasses and conventional forages become scarce [8-10] . Beyond their value as dry-season feed, these species enrich farming systems through atmospheric nitrogen fixation, which supports soil fertility, and by promoting improved water retention and erosion control. Their integration into mixed crop-livestock systems can therefore simultaneously address feed deficits and contribute to agroecological sustainability.

Studies of browse species across tropical regions have revealed considerable variation in their chemical composition, with many species demonstrating crude protein contents ranging from 12% to over 24%, along with meaningful mineral and fibre fractions [8-14]. However, the nutritional value of browse can fluctuate substantially with season, species, plant part, and growing conditions. Furthermore, antinutritional factors such as condensed tannins, oxalates, and phytates, while sometimes beneficial for rumen protein protection or gastrointestinal parasite control, must be evaluated and managed to ensure optimum feed utilisation [8, 9]. Feed evaluation for alternative resources increasingly employs standardised laboratory methods, including proximate analysis, fibre fractionation (ADF/NDF), mineral profiling, and in vitro/in situ digestibility assessment, to determine feed value and safety. *In vitro* digestibility approaches, in particular, enable cost-effective and rapid screening of multiple feed samples, while analysis of antinutritional compounds guides appropriate processing and safe inclusion rates [15].

Mixed crop-livestock systems, such as those practised in the Linden area of Region Ten (Upper Demerara-Berbice), Guyana, derive substantial benefit from integrating browse resources, as this supports both animal nutrition and ecological resilience [10]. Despite the centrality of browse species in dry-season feeding regimes among smallholders in this region, there remains limited documentation on the specific types, seasonal availability, and nutritive value of indigenous browse in Guyana. Previous regional studies have been sparse, and the lack of comprehensive nutritional evaluation constrains effective utilisation and wider adoption. While browse species have proven valuable in livestock feeding systems elsewhere in the tropics, there is a notable paucity of detailed scientific information on indigenous browse resources in the Linden region. Specifically, data on chemical composition, mineral profiles, and the relationship between soil fertility and foliar nutrient content are lacking, representing a significant knowledge gap that limits evidence-based feeding recommendations for smallholder livestock producers.

The study was therefore designed to address this knowledge gap by systematically evaluating the nutritional composition and feeding potential of indigenous browse species for livestock in the mixed crop-livestock systems of Linden, Region Ten. The specific objectives of this study were to: (1) determine the proximate composition (crude protein, crude fibre, fat, ash, and moisture) of leaf meals from eleven indigenous browse species commonly utilised or available in the study area; (2) quantify the mineral content (calcium, potassium, sodium, and zinc) of leaf meals from these species; (3) characterise the physical and chemical properties of soils at browse species collection sites to assess soil fertility status and its potential influence on foliar nutrient content; and (4) evaluate interspecies differences in nutritional parameters to identify browse species with the most favourable nutritional profiles for supplementary livestock feeding.

2. Materials and Methods

2.1. Study location

The study was conducted in the Linden area of Upper Demerara-Berbice (Region #10), Guyana, centred at approximately 6°02′04.25″N, 58°18′19.24″W. Field surveys and sample collection were carried out in four communities: Amelia's Ward, Christiansburg, Wisroc, and West Watooka. These communities were selected on the basis of their established mixed crop-livestock farming activities, the documented presence of diverse indigenous browse species, and accessibility for repeated sampling visits. The research area is densely populated relative to Guyana's interior regions and is surrounded by abundant secondary and disturbed vegetation, providing a rich mosaic of browse plant resources.

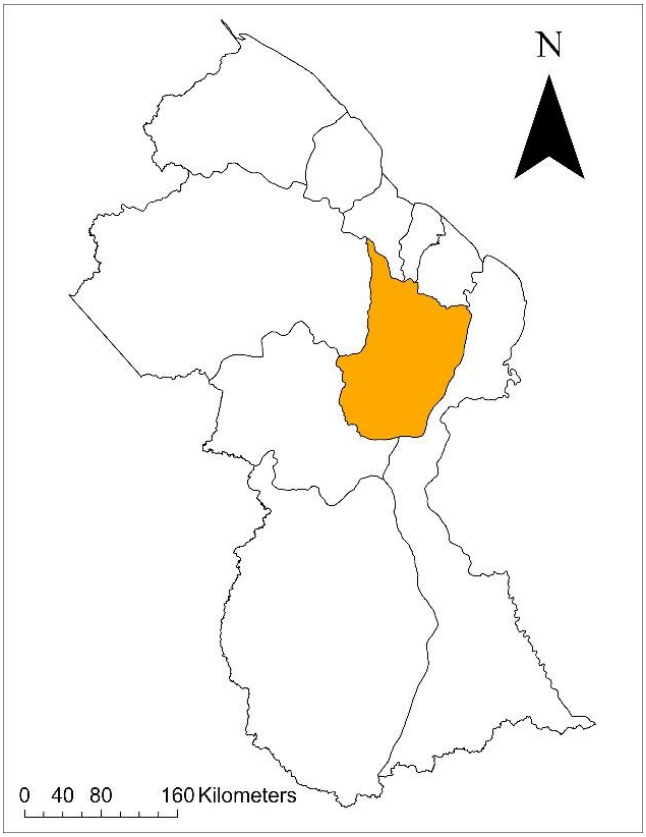

Figure 1. Map of Upper Demerara- Berbice (Region # 10) Linden.

The study area is classified under the Köppen–Geiger system as a tropical rainforest climate (Af), characterised by consistently high temperatures and rainfall throughout the

year with no pronounced dry season [16, 17]. Mean annual air temperature is approximately 26.8 °C, with mean monthly temperatures ranging from 25.6 °C (February) to 27.8 °C (September–October). Mean daily maximum temperatures vary from 30.0 °C to 33.3 °C, while mean daily minimum temperatures range from 21.1 °C to 22.8 °C, reflecting the low thermal seasonality typical of equatorial lowland environments. Mean annual rainfall is approximately 2,164 mm, distributed bimodally with a primary wet season from May to August (monthly totals of 217–317 mm) and a secondary wet season from November to January (154–228 mm). Two relatively drier periods occur from February to April (90–142 mm per month) and from September to October (111–112 mm per month), although rainfall is never absent in any month. Mean annual relative humidity is approximately 86%, ranging from 82% in March to 89% in June [50]. Sample collection was conducted during the primary wet season (May–August) to coincide with peak vegetative growth and foliar nutrient accumulation, thereby standardising the phenological stage at which browse species were sampled.

The predominant soil types at the study locations consist of alluvial and Loring sandy soils, which are moderately well drained. These soil types are typical of the riverine and low-lying terraces along the Demerara River and its tributaries in Region 10. The slightly acidic nature of these soils (pH 5–6), as confirmed by the soil analysis results of this study, is consistent with the leached, weathered tropical soils commonly found in the Guiana Shield region [18, 19].

2.2. Soil analysis procedure

2.2.1. Soil sample collection and preparation

Soil samples were collected from a total of seven (7) sampling sites distributed across the four study communities: two sites each in Christiansburg, Wisroc, and Amelia's Ward, and one site in West Watooka (Figure 1; Figure S1). Sampling sites were selected to correspond to the locations where browse species were collected, ensuring that soil fertility data could be directly related to the foliar nutrient composition of the sampled plants.

The soil sampling methfodology was adopted from [20, 21] with slight modifications to suit the local field conditions and study objectivesAt each of the seven sites, soil sampling was carried out at a depth of 0–20 cm using a stainless steel soil auger to target the active root zone where nutrient uptake by browse species predominantly occurs [22]. A zigzag (W-pattern) sampling transect was followed at each site to ensure adequate spatial coverage, with 5–10 subsamples collected at approximately equal intervals along the transect [20, 21]. The subsamples from each site were thoroughly mixed in a clean polyethylene bucket to form a single composite sample per site [23]. This compositing procedure was replicated three times at each site, that is, three independent composite samples were prepared per site by conducting three separate zigzag traversals yielding a total of 21 composite soil samples (7 sites × 3 replicates). Each composite sample was clearly labelled with the date, community name, site identification number, and sampling depth (0–20 cm).

Following collection, soil samples were transported to the laboratory in sealed polyethylene bags and air-dried in a shaded, well-ventilated area for 2–3 days until moisture equilibrium was reached. After drying, the samples were gently crushed using a porcelain mortar and pestle and passed through a 2-mm stainless steel sieve to remove coarse fragments, plant debris, and gravel, thereby ensuring uniform particle size for chemical analysis. For micronutrient analysis (including DTPA-extractable zinc), a portion of each sieved sample was further ground and passed through a 0.5-mm mesh sieve. Prepared samples were stored in labelled, sealed plastic containers at room temperature until analysis.

Table 1. Soil sample identification codes, corresponding browse species, community locations, and GPS coordinates for the seven sampling sites in the Linden area, Region 10, Guyana.

Sample Code	Site No.	Species Abbr.	Browse Species Present	Community	GPS Coordinates
SSKCL1QS	1	QS	Quick Stick (*Gliricidia sepium*)	Christiansburg	6.016807, −58.303278
SSKCL2P	2	P	Papaya (*Carica papaya*)	Christiansburg	5.998730, −58.331139
SSKCL3SA	3	SA	Carrion crow bush (*Senna alata*)	Wisroc	6.018553, −58.302416
SSKCL4M	4	M	Cassava (*Manihot esculenta*)	Wisroc	6.000693, −58.336023
SSKCL5RB	5	RB	Showy Rattlebox (*Crotalaria spectabilis*)	Amelia's Ward	6.008130, −58.302219
SSKCL6RT	6	RT	Rain Tree (*Samanea saman*)	Amelia's Ward	5.9952, −58.2698
SSKCL7CSP	7	CSP	Cassava + Sweet Potato (*Manihot esculenta* + *Ipomoea batatas*)	West Watooka	6.024540, −58.271711

2.3 Collection and processing of plant materials

2.3.1 Collection process - species selection criteria

A total of eleven (11) browse species were selected for this study based on a multi-criteria approach. An initial reconnaissance survey was conducted across the communities of Christiansburg, Wisroc, West Watooka, and Amelia's Ward in the Linden area of Upper Demerara-Berbice (Region #10) to identify plant species commonly browsed by or accessible to livestock. Species were considered eligible for inclusion if they met the following criteria: (i) documented or observed utilisation as livestock feed by smallholder farmers in the study area, as ascertained through informal discussions with local livestock keepers during the preliminary field survey; (ii) widespread local abundance and accessibility, ensuring that the species could realistically serve as a supplementary feed resource; (iii) prior documentation in published literature as a browse or forage species with recognised nutritional potential for ruminant livestock [8, 9, 11]; and (iv) representation of a range of plant growth forms (herbaceous plants, shrubs, and trees) and botanical families (Fabaceae, Araceae, Euphorbiaceae, Convolvulaceae, and Caricaceae) to capture the diversity of indigenous browse resources available in the region.

Candidate species identified during the reconnaissance survey were cross-referenced against published ethnobotanical and feed evaluation studies from the Caribbean and wider tropical regions to confirm their relevance as livestock browse [8, 9, 11]. From the pool of candidate species, the following eleven were selected: Senna alata (L.) Roxb. (carrion crow bush), *M. esculenta* Crantz (cassava), *C. spectabilis* DC. (showy rattlebox), *G. sepium* (Jacq.) Walp. (quick stick), *C. esculenta* (L.) Schott (taro), *C. papaya* L. (papaya), *I. batatas* (L.) Lam. (sweet potato), *P. montana* (Lour.) Merr. (kudzu), *D. intortum* (Mill.) Urb. (Greenleaf desmodium), *Lysiloma latisiliquum* (L.) Benth. (false tamarind), and *S. saman* (Jacq.) Merr. (rain tree). These species encompassed five leguminous taxa (*S. alata*, *C. spectabilis*, *G. sepium*, *D. intortum*, and *S. saman*) and six non-leguminous species, thereby allowing a comparative assessment of nutritional profiles across taxonomically and functionally diverse browse resources.

2.3.2 Sampling procedure

A stratified random sampling design was employed to ensure representative and unbiased collection of plant material [24, 25]. The four study communities (Christiansburg, Wisroc, West Watooka, and Amelia's Ward) were designated as sampling strata to account for potential spatial variation in browse species distribution and growing conditions [24]. Within each community, collection sites where the target species occurred were identified during the preliminary survey and georeferenced using a handheld GPS receiver [26]. For each species at each community, individual plants were assigned sequential identification numbers, and three plants per species were randomly selected using a random number table to serve as biological replicates, yielding a total of 33 sampling units (11 species × 3 replicates). Where a species was present in more than one community, replicate plants were distributed across communities to maximise spatial representation and capture potential variation attributable to local edaphic or microclimatic conditions [24, 27].

Leaf samples were collected from each randomly selected plant during the wet season to standardise the phenological stage at harvest [28, 29]. For each replicate, mature, fully expanded leaves free of visible disease, pest damage, or senescence were harvested from the upper, middle, and lower canopy levels and pooled to form a single composite sample per replicate per species. This canopy-level pooling strategy was adopted to minimise within-plant variability in nutrient concentration, as foliar chemistry can differ with leaf age and light exposure [30, 31]. Samples were placed in labelled polyethylene bags, stored in a cooler with ice packs, and transported to the University of Guyana, Greater Georgetown, within 24 hours of collection for further processing and analysis. Corresponding soil samples were collected from the root zone of each sampled plant at a depth of 0–20 cm (described in the Soil Analysis Procedure section below).

2.3.4 Processing of leaf meal

Upon arrival at the laboratory, leaves were thoroughly washed with distilled water to remove surface soil, dust, and other extraneous material. Washed leaves were subsequently soaked in distilled water at ambient temperature (~28 °C) for 24 hours at a leaf-to-water ratio of approximately 1:10 (w/v). This soaking step was incorporated as a pre-treatment to reduce the concentration of water-soluble antinutritional factors, including tannins, oxalates, phytates, and cyanogenic glycosides, that are commonly present in tropical browse species and that can impair nutrient bioavailability and feed utilisation if left untreated [32-34]. Soaking in distilled water has been shown to significantly decrease the levels of these soluble antinutrients through passive diffusion and leaching into the soaking medium. For instance, soaking in distilled water has been reported to reduce total phenols, tannins, and phytates by 21–56% depending on the plant material and soaking duration [35]. A 24-hour soaking period was selected as it represents a widely adopted processing duration in tropical feed and food preparation studies, providing effective antinutrient reduction while minimising excessive leaching of desirable nutrients such as water-soluble vitamins and minerals. It is acknowledged that prolonged soaking may result in partial loss of some soluble nutrients; however, the primary objective of this pre-treatment was to render the leaf meals safer and more representative of the form in which they would be offered to livestock following on-farm processing. The soaking water was discarded after 24 hours, and the leaves were rinsed once with fresh distilled water before proceeding to the drying stage.

The total harvested material for each replicate was weighed fresh, and an approximately 1-kg subsample was taken and dried at 55 °C for 72 hours in a forced-air oven (Memmert UF110, Memmert GmbH, Schwabach, Germany) until constant weight was achieved. A drying temperature of 55 °C was selected to preserve heat-labile constituents, particularly nitrogen-containing compounds and vitamins,

while achieving adequate moisture removal for stable storage and subsequent grinding.

After drying, samples were ground using an Original Thomas Scientific Wiley Mill (Model 4) fitted with a 1-mm stainless steel mesh screen (20-mesh equivalent). All samples were ground to pass through this 1-mm screen to ensure uniform particle size distribution, which is a prerequisite for both near-infrared reflectance spectroscopy (NIRS) analysis and conventional wet chemical procedures [47, 48]. The 1-mm particle size specification conforms to the laboratory sample preparation guidelines recommended by the Association of Official Analytical Chemists (AOAC) and the National Forage Testing Association (NFTA), which stipulate that forage and feed samples intended for proximate analysis and NIRS scanning must be ground to pass a 1-mm sieve using a cutting mill (Wiley or equivalent) [36, 37]. Ground samples were thoroughly homogenised, transferred to airtight polyethylene containers, and stored in a desiccator at room temperature until analysis to prevent reabsorption of atmospheric moisture.

Ground leaf meal samples were analysed for proximate composition, including ash, moisture, crude protein, dry matter, starch, acid detergent fibre (ADF), and neutral detergent fibre (NDF), using near-infrared reflectance spectroscopy (NIRS). Mineral content (calcium, potassium, sodium, and zinc) was determined by atomic absorption spectrophotometry (AAS) following wet acid digestion of the leaf meal according to standard procedures [38, 39].

2.3.5 Soil sample identification and site description

Soil sample identification codes follow a standardised labelling convention designed to link each soil sample to a specific collection site, the dominant browse species present at that site, and the community in which sampling was conducted. Each code begins with the prefix SSKCL, where SS denotes “Soil Sample” and KCL is the project area code. This prefix is followed by a numeric site identifier (1–7) and a species abbreviation derived from the common name of the dominant browse species at that location. For example, SSKCL1QS denotes the soil sample from Site 1, where Quick Stick (*G. sepium*) was the dominant browse species, while SSKCL7CSP represents Site 7, where both Cassava (*M. esculenta*) and Sweet Potato (*I. batatas*) were present. The seven sampling sites are distributed across the four study communities: Christiansburg (2 sites), Wisroc (2 sites), Amelia’s Ward (2 sites), and West Watooka (1 site). Table 1 provides the full designation for each soil sample code, including the site number, species abbreviation, browse species present, community, and GPS coordinates (Table S2).

2.4. Laboratory procedures for determining key physical and chemical soil parameters

2.4.1 Physical methods

Soil texture is commonly determined via the hydrometer method, where soil samples were dispersed with sodium hexametaphosphate, shaken, and allowed to settle; the relative proportions of sand, silt, and clay were then measured by a hydrometer with slight modifications [40]. Bulk density was assessed by collecting undisturbed cores, oven-drying at 105°C, weighing, and dividing dry mass by core volume [41].

2.4.2 Chemical methods

Soil pH was measured by mixing soil with distilled water in a 1:2.5 ratio, letting it settle, and reading with a calibrated electrode with slight modification [42]. Electrical conductivity (EC) uses the same extract and an EC meter [43]. Organic carbon is determined by the Walkley-Black method, involving oxidation with potassium dichromate and sulfuric acid, followed by titration [44]. Total nitrogen is measured by the Kjeldahl method, which involves acid digestion, distillation, and titration [45, 46].

Available phosphorus was extracted using Olsen’s method with slight modification (for neutral/alkaline soils) or Bray’s method (for acidic soils), and measured with spectrophotometry [47, 48]. Exchangeable potassium and sodium are extracted with ammonium acetate, determined by flame photometry or atomic absorption spectrophotometry (AAS) [49-51]. Micronutrients like Fe, Mn, Zn, and Cu are extracted using DTPA and analyzed by AAS [38, 39].

2.4.3 Data recording and interpretation

All measurements were recorded in a standardized data sheet. The results were compared with established critical values for soil fertility to interpret the nutrient status of each location. Spatial variability was visualized by mapping the data where applicable.

2.4.4 Quality control

Quality control measures were applied throughout the process. Blank samples, standards, and replicates were included to ensure accuracy. Instruments were calibrated regularly, and all laboratory glassware and tools were kept clean to avoid contamination.

2.4.5 Safety and laboratory practice

All laboratory work was conducted following standard safety protocols. Personal protective equipment (PPE), including gloves and lab coats, was worn, and all chemical waste was disposed of according to environmental regulations.

2.5 Statistical analysis

All data were expressed as means ± standard error based on triplicate determinations (N = 3 per species). Nutritional composition data for the eleven browse species were subjected to a one-way Analysis of Variance (ANOVA) using a completely randomized design (CRD) to test for significant differences among species for each proximate and mineral parameter. The fixed factor was plant species (k = 11), with degrees of freedom of 10 (between groups) and 22 (within groups). Statistical significance was set at $p < 0.05$. Where the ANOVA indicated significant differences, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied for pairwise comparisons among all species means. Effect sizes were calculated using eta-squared (η^2) to quantify the

magnitude of interspecies variation for each parameter.

Pearson correlation analysis was performed to examine relationships among the nutritional parameters. Principal component analysis (PCA) was conducted to identify the major sources of variation and to explore multivariate relationships among species based on their nutritional profiles. ANOVA and Tukey HSD analyses were performed using the Statistix 10 software package (Analytical Software, Tallahassee, FL, USA). All other statistical analyses were performed with R statistical software version 4.4.3 [52] and the packages *'ggplot2'* [53], *'Metrics' 'Metrics'* [54], *'Rmisc'* [55], and *'corrplot'* [56].

3. Results

3.2 Variation in proximate composition among species

The proximate composition of the eleven browse species is presented in Figure 2A-E. Significant differences among species were observed for all proximate parameters ($p < 0.001$), including crude protein, moisture, fat, fibre, and ash content. Crude protein content varied substantially across species, ranging from approximately 186,400 mg/kg in *C. papaya* to 281,200 mg/kg in *M. esculenta*. Similarly, Ipomoea batatas and *G. sepium* exhibited high protein concentrations, indicating their strong potential as protein-rich feed resources (Figure 2A). In contrast, relatively lower protein levels were observed in species such as *Carica papaya*, though still within nutritionally relevant ranges.

Moisture content showed comparatively limited variation among species, generally ranging between 75,000 and 89,000 mg/kg (Figure 2B). The highest moisture levels were recorded in *C. esculenta* and *C. spectabilis*, whereas other species exhibited slightly lower but comparable values. Fat content demonstrated pronounced variability, with the lowest values observed in *C. spectabilis* (~30,000 mg/kg) and the highest in *S. alata* and *C. papaya* (approaching 60,000 mg/kg) (Figure 2C). This indicates species-specific differences in energy contribution potential. Fibre content also differed markedly, with *P. montana* and *S. saman* recording the highest values (>160,000 mg/kg), while *M. esculenta* and *C. esculenta* showed the lowest fibre concentrations (<90,000 mg/kg) (Figure 2D). Ash content followed a similar pattern of variation, with *C. esculenta* and *S. saman* exhibiting the highest mineral content (>110,000 mg/kg), whereas *D. intortum* showed comparatively lower values (Figure 2E).

3.3 Variation in mineral composition among species

Figure 3 presents the mineral composition of the browse species, revealing significant variation for sodium and zinc ($p < 0.001$), while calcium and potassium did not differ significantly among species ($p > 0.05$).

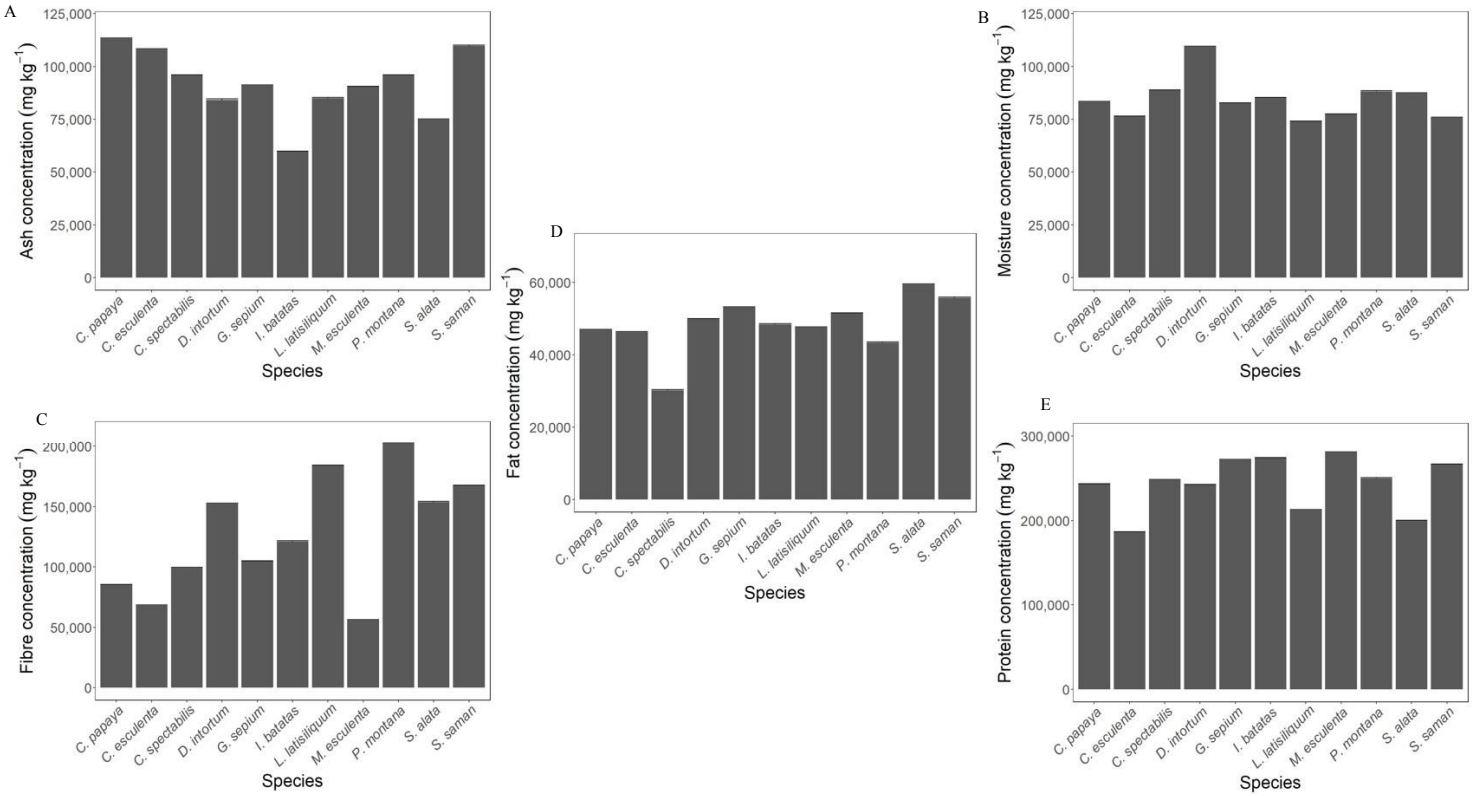

Figure 2. Comparative analysis of proximate composition across plant species. Mean concentrations of (A) ash, (B) moisture, (C) fat, (D) fiber, and (E) protein are shown for each species. Different letters (a, b, c, d, e) indicate statistically significant differences ($p < 0.05$) according to the Tukey HSD test.

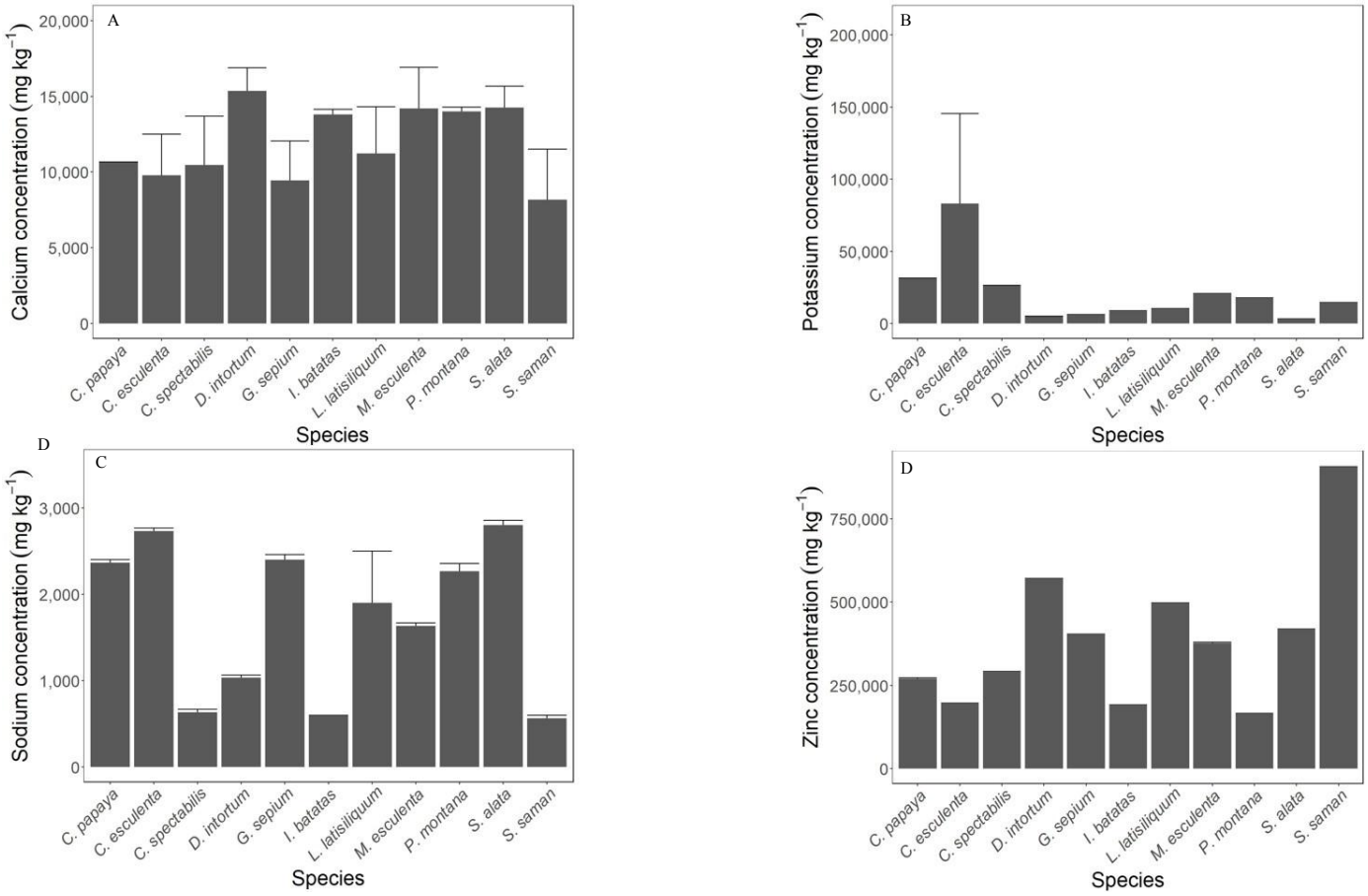

Figure 3. Comparison of mineral concentrations across plant species Mean concentrations of (A)calcium, (B) potassium, (C) sodium, and (D) zinc are shown for each species. Different letters indicate statistically significant differences ($p < .05$) using TukeyHSD test between species.

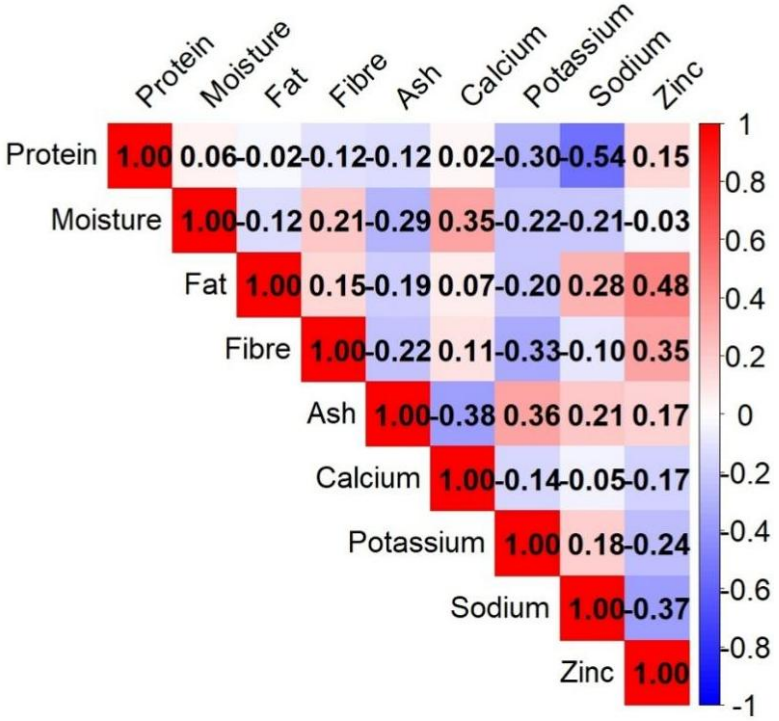

Figure 4. Pearson correlations between species proximate and mineral parameters.

Calcium concentrations were highest in *M. esculenta*, reaching approximately 18,900 mg/kg, whereas *S. saman* and *G. sepium* exhibited the lowest levels (Figure 3A). Potassium content was generally high across all species, with *C. esculenta* showing the highest concentration (~31,300 mg/kg), followed by *C. spectabilis*. Lower potassium levels were observed in *C. papaya* and *G. sepium* (Figure 3B).

Sodium concentrations were relatively low across all species, ranging from approximately 600 mg/kg to 4,800 mg/kg (Figure 3C). The highest sodium content was recorded in *D. intortum*, whereas *C. spectabilis* and *S. saman* had the lowest values.

Zinc exhibited the greatest variability among all minerals. *S. saman* showed exceptionally high zinc concentrations (>900,000 mg/kg), while *P. montana* and *I. batatas* recorded the lowest values (<200,000 mg/kg), indicating strong interspecific differences in micronutrient accumulation (Figure 3D).

3.4 Correlation among nutritional parameters

The Pearson correlation matrix shown in figure 4 highlights the relationships among proximate and mineral parameters. A moderate negative correlation was observed between crude protein and sodium ($r = -0.54$), suggesting that species with higher protein content tend to have lower sodium levels.

In contrast, a moderate positive correlation was identified between fat and zinc ($r = 0.48$), indicating a tendency for higher fat content to be associated with increased zinc accumulation. Most other relationships were weak, indicating that nutritional traits varied largely independently across species.

3.5 Multivariate analysis of nutritional profiles

Principal component analysis (PCA) results are presented in figure 5. The first principal component (PC1) explained 26.12% of the total variance, while the second component (PC2) accounted for additional variation, together summarizing a substantial proportion of the dataset variability. The PCA biplot illustrates clear separation among species based on their nutritional profiles, indicating distinct compositional differences. Species positioned along the positive axis of PC1 were associated with higher values of specific nutritional parameters, while others clustered separately, reflecting contrasting nutrient compositions.

3.6 Soil physicochemical properties across sites

Figure 6 presents the variation in soil properties across the seven sampling sites. Soil pH ranged from moderately acidic to slightly acidic (approximately 4.9–6.1), reflecting typical tropical soil conditions. Organic matter content showed considerable variation among sites, indicating differences in soil fertility. Similarly, cation exchange capacity (CEC) varied across locations, reflecting differences in nutrient retention potential. Macronutrient concentrations, including calcium and potassium, as well as micronutrients such as zinc and iron, also differed among sites, highlighting spatial heterogeneity in soil nutrient availability.

3.7 Comparison between soil and plant nutrient concentrations

Figure 7 compares nutrient concentrations in soil and plant tissues. Across all species, plant nutrient concentrations were generally higher than those in the corresponding soils, indicating active nutrient uptake and accumulation. This pattern was particularly evident for micronutrients such as zinc, where plant concentrations greatly exceeded soil levels.

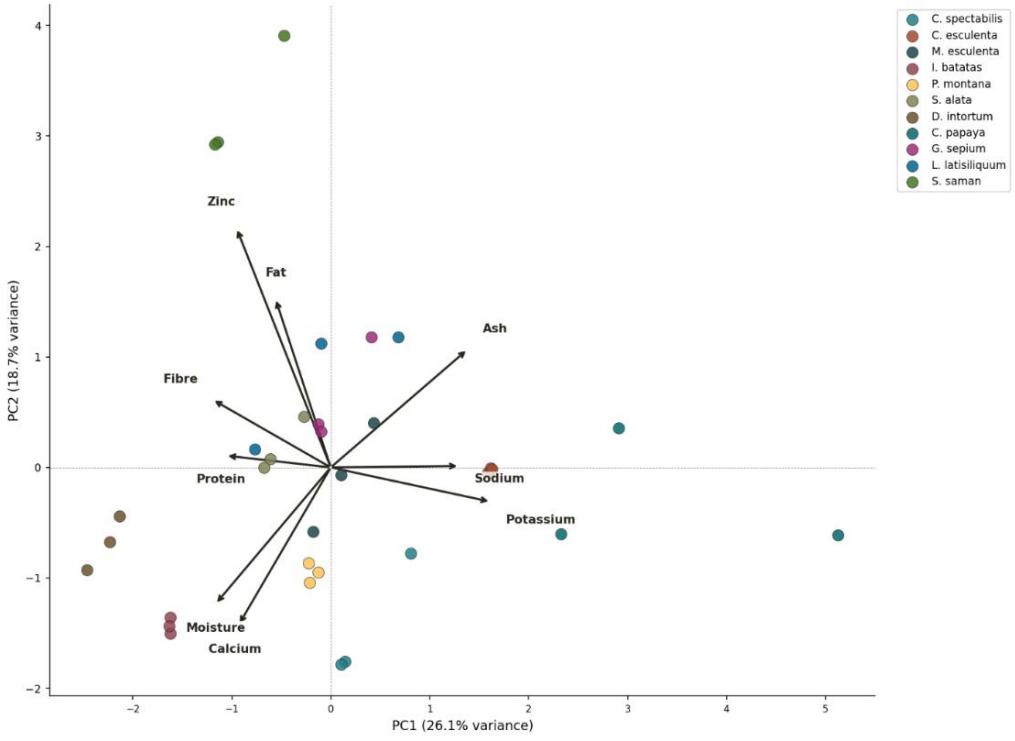

Figure 5. PCA biplot showing species distribution by nutrient profile (mg/kg) and variable loadings (PC1 vs PC2).

The results suggest that the studied species possess strong nutrient accumulation capabilities, particularly for trace elements.

3.8 Correlation among soil properties

The correlation matrix of soil properties is presented in figure 8. Soil pH showed relationships with the availability of several nutrients, particularly micronutrients, which tend to increase under more acidic conditions. Organic carbon and cation exchange capacity were positively correlated, indicating that soils with higher organic matter content had greater nutrient retention capacity. Additional relationships among macronutrients and micronutrients reflect the complex interactions governing soil fertility and nutrient dynamics across the study sites.

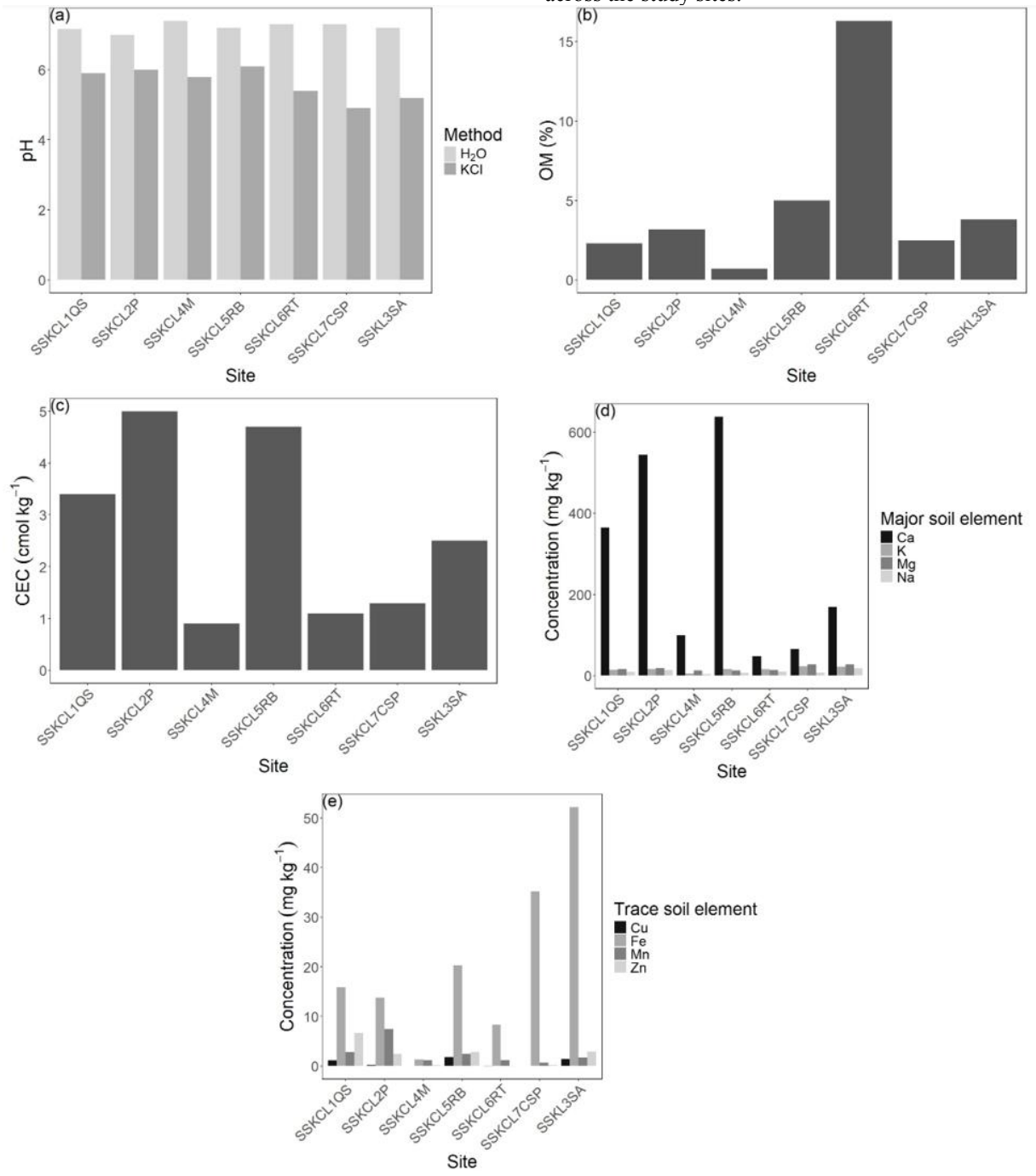

Figure 6. Key soil properties across seven collection sites, (a) pH levels, (b) organic matter (OM), (c) cation exchange capacity (CEC), (d) major soil elements, and (e) trace soil elements. The grouped bar format compares parameters side-by-side for easy site-to-site analysis.

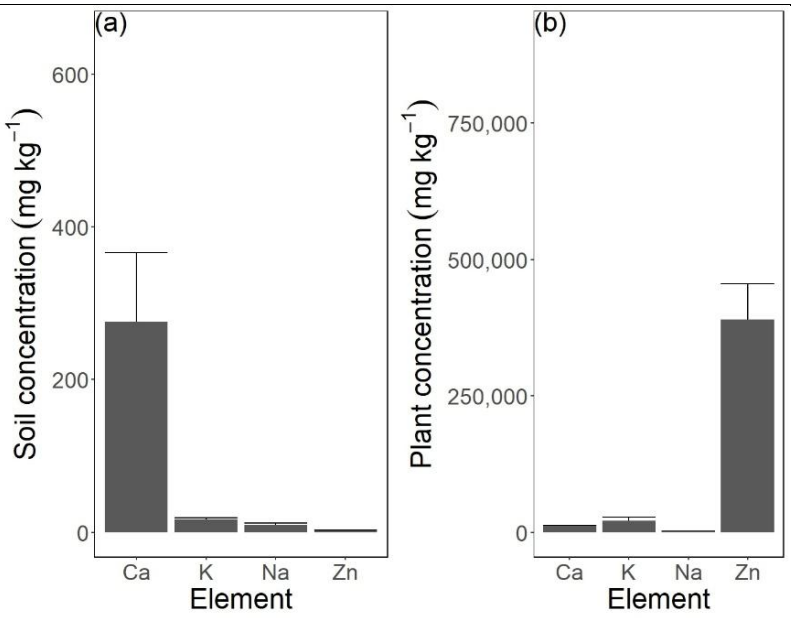

Figure 7. Comparison of (a) soil and (b) plant element concentrations. Error bars indicate mean ± SE. Different letters indicate statistically significant differences ($p < .05$) using TukeyHSD test between species.

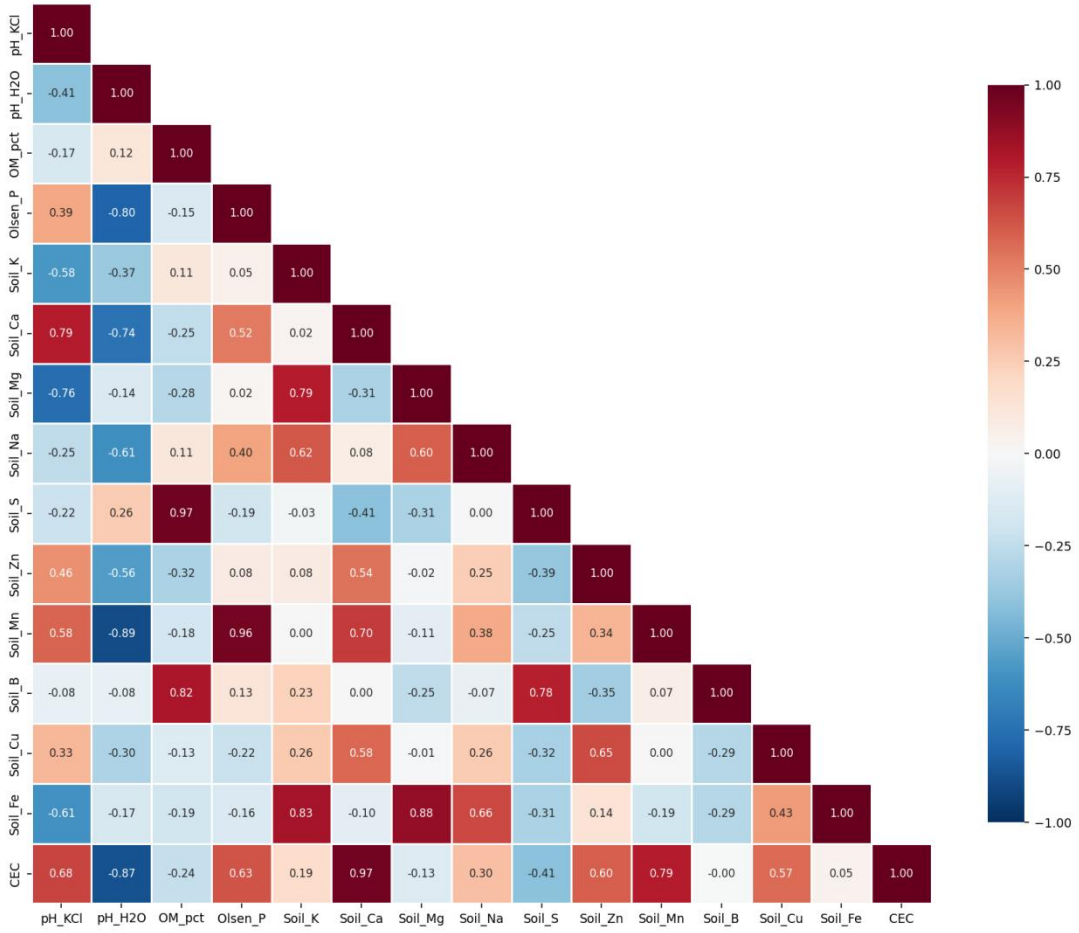

Figure 8. Pearson correlations heatmap among soil properties like pH, organic carbon (OC), nitrogen (N), phosporous (P), potassium (K), sodium (Na), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), and cation exchange capacity (CEC).

4. Discussion

The results demonstrated considerable variability in nutrient composition across the eleven browse species evaluated as potential alternative livestock feeds. Crude protein (CP) concentrations ranged from 186,400 mg/kg (18.64%) in *C. papaya* to 281,200 mg/kg (28.12%) in *M. esculenta*, with *I. batatas* (27.39%), *G. sepium* (27.22%), and *S. saman* (26.65%) also exhibiting high protein levels. These values compare favourably with those reported in the wider tropical browse literature. For instance, *G. sepium* foliage has been reported to contain 18–30% CP with an in vitro digestibility of 60–65% [57-59], and the protein content recorded in the present study (27.22%) falls within the upper range of those values. Similarly, the CP of *M. esculenta* leaf meal in this study (28.12%) is consistent with the range of 21–26% reported by the Food and Agriculture Organization of the United Nations (FAO) and the 22–23% recorded at various altitudes in West Java, though slightly higher, possibly reflecting differences in cultivar, leaf maturity, or growing conditions. The CP content of *I. batatas* leaf meal (27.39%) exceeds the 24.21% reported by Council et al. [60] and is considerably higher than the 2.99 g/100 g fresh weight reported by Ruminants et al. [59], a discrepancy attributable to the use of dried leaf meal in the present study versus fresh weight in the latter. These findings collectively confirm that several of the browse species evaluated in the Linden area possess CP concentrations sufficient to meet or exceed the maintenance requirements (7–10% CP) and lactation requirements (12–18% CP) for cattle, sheep, and goats [59, 60] (Figure 2).

Fibre content varied markedly among species, with *P. montana* (20.27%) and *S. saman* (16.75%) recording the highest values, while *M. esculenta* (5.64%) and *C. esculenta* (8.54%) had the lowest. The fibre content of *P. montana* is consistent with the 13–40% range reported for kudzu hay and leaf fractions [13, 14, 63-67] and aligns with the observation that kudzu leaves are a good-quality forage source when fibre content falls below 70% NDF [68]. High-fibre species such as *P. montana* and *S. saman* are valuable for promoting rumen health and gut motility in ruminants, whereas lower-fibre species like *M. esculenta* offer higher energy density, suggesting complementary roles in strategic feed formulation. Fat content ranged from 3.02% in *C. spectabilis* to 5.96% in *S. alata*, values broadly consistent with those reported for tropical browse legumes and forbs. Moisture content was relatively uniform (7.04–10.96%), indicating consistent drying protocols across all species (Figure 2).

Mineral composition showed notable inter-species variation (Figure 3). Calcium content was highest in *D. intortum* (1.54%) and *S. alata* (1.43%), while potassium was most concentrated in *C. esculenta* (3.13%). The high potassium content of *C. esculenta* is consistent with the known mineral-rich profile of taro leaves, which have been reported to contain 20.5% CP and serve as a valuable protein and mineral supplement for monogastric and ruminant animals [69-72]. *D. intortum* is recognised as having high foliage CP (16–22%) with moderate palatability due to condensed tannins and the calcium concentration observed in this study supports its role as a mineral-dense supplement. Sodium content was generally low across all species (0.06–0.24%), consistent with the typically low sodium levels in tropical forages, which may necessitate mineral supplementation in livestock diets.

Zinc concentrations varied substantially, with *S. saman* recording an exceptionally high value of 90.74 mg/kg, followed by *D. intortum* (57.08 mg/kg) and *L. latisiliquum* (49.81 mg/kg), while *P. montana* (16.56 mg/kg) and I. batatas (19.20 mg/kg) showed the lowest levels. Cross-analysis of plant tissue and soil mineral data revealed that all species were net accumulators (bioconcentration factor [BCF] > 1) for calcium, potassium, sodium, and zinc. Zinc showed extraordinary hyperaccumulation across all species, with mean BCF values of approximately 177,000. Notably, *S. saman* exhibited the highest zinc BCF of 411,478, raising potential feed safety concerns. Given that zinc concentrations in S. saman leaf meal exceed safe dietary thresholds for livestock, caution is advised when incorporating this species into feeding regimes, and further investigation of zinc toxicity risks is recommended [73, 74] (Figures 3 and 4).

A critical finding of this study is the relationship between soil fertility parameters and the nutritional composition of the browse species (Figure 8). The slightly acidic soil pH (4.9–6.1) observed across the seven sampling sites is consistent with the leached, weathered tropical soils of the Guiana Shield region and has direct implications for nutrient availability and plant uptake. Soil pH is widely regarded as the "master variable" of soil chemistry, governing the solubility and bioavailability of essential plant nutrients [75]. In slightly acidic soils (pH 5–6), the availability of micronutrients such as zinc, manganese, copper, and iron increases with decreasing pH (Figure 6), which may explain the elevated zinc concentrations observed in the browse species, particularly at SSKCL7CSP (pH 4.9) and SSKCL6RT (pH 5.4), where soil zinc was lowest (≤0.2 ppm) yet plant tissue zinc was high, suggesting highly efficient uptake mechanisms at lower pH.

Organic matter (OM) content varied widely across sites, from 0.7% at SSKCL4M to 16.3% at SSKCL6RT, with corresponding differences in cation exchange capacity (CEC; 0.9–5.0 meq/100 g). These differences reflect the heterogeneity of soil types across the Linden study area, which includes sandy Regosols, Red Yellow Podzolic soils, and organic pegasse soils. Sites with higher OM and CEC (SSKCL2P, SSKCL5RB) generally exhibited greater concentrations of exchangeable cations, including calcium and potassium, which are essential for plant mineral uptake and, consequently, for the mineral quality of browse foliage consumed by livestock [67, 76]. Mudau et al. [8] reported significant differences in the CP and mineral content of 52 browse species harvested from two contrasting soil types in semi-arid South Africa, demonstrating that harvesting site and by extension, soil fertility, directly influences browse nutritional quality [8]. Similarly, Niu et al. [77] showed that tradeoffs exist between forage quality and soil fertility in Himalayan rangelands, with forage nitrogen content increasing on more fertile soils but at the cost of reduced species diversity [77] (Figures 6 and 7).

Available phosphorus was notably elevated at SSKCL2P (48 mg/kg), the site associated with *C. papaya* in Christiansburg, compared with the remaining six sites (1–3 mg/kg). Phosphorus deficiency is recognised as a major constraint to the growth and productivity of tropical forages on low-fertility acid soils [28, 76, 78] and the low phosphorus levels at most sites in this study may limit the nutrient density of browse foliage, particularly protein synthesis, which is strongly phosphorus-dependent. This is consistent with the observation that *C. papaya* recorded the lowest CP (18.64%) despite growing at the site with the highest available P, suggesting that species-specific physiological traits and other edaphic factors (e.g., nitrogen availability, mycorrhizal associations) also govern foliar nutrient composition. The wide variation in soil potassium (6–23 mg/kg) and calcium (48–638 mg/kg) across sites further underscores that site-specific soil fertility conditions influence the mineral composition of browse foliage, which has downstream consequences for the mineral nutrition of livestock grazing these species (Figure 6).

The ash content, indicative of total mineral matter, identified *C. esculenta* (11.35%) and *S. saman* (10.97%) as the most mineral-rich species, while *I. batatas* (5.97%) had the lowest ash content. The relatively high ash values in *C. esculenta* correspond with its elevated potassium (3.13%) and calcium (1.06%) concentrations, reinforcing its potential as a mineral supplement in livestock diets (Figures 2 and 3). These results are consistent with the broader finding that foliar mineral concentrations in tropical browse species are governed by the interplay between soil nutrient availability, species-specific uptake efficiency, and environmental conditions such as pH, OM, and CEC [8, 28, 78] (Figure 6). The present study therefore provides baseline data linking soil fertility status across the four study communities in Linden to the nutritional profiles of indigenous browse species, highlighting the importance of site-specific soil management for optimising forage quality in mixed crop-livestock systems.

5. Conclusion

In conclusion, the data demonstrate that targeted use of alternative plant feed resources can address nutritional gaps, enhance animal performance, reduce feed costs, and promote sustainable agriculture through diversification and locally adapted species integration, consistent with trends emphasizing food system resilience. The considerable nutrient diversity among the 11 species offers opportunities for tailored feed mixtures to meet production goals while sustaining health and minimizing environmental impact. Future research should prioritize controlled field trials on livestock growth/productivity, in vivo/in vitro digestibility and bioavailability of key nutrients (proteins, minerals like hyperaccumulated zinc), soil-plant correlations with amendments (e.g., organics, microbes), economic or environmental assessments of feed incorporation, varietal breeding for yield/nutrition/resilience, and farmer adoption studies via demonstrations and workshops to overcome barriers and enable widespread use in Guyana's tropical systems.

Author contributions

Ewart Smith: Writing-original draft, Methodology, Formal analysis and investigation, Data Analysis, Data Curation. Abiola Bruce -Smith: Conceptualization of main focus of the paper, Methodology, Data Analysis, Data Curation, Writing Review and Editing. Samantha Providence - Forrester: Conceptualization of main focus of the paper, Collection of leaf samples, Writing-Review and Editing, Supervision. Neveen Gray: Conceptualization of main focus of the paper, Data curation, Writing-Review and Editing. Chetwynd Osborne: Data Analysis, Data Curation, Map development, Writing-Review and Editing. Kimberly Coppin: Collection of leaf and soil samples, Data Curation, Data Analysis, GPS data collection, Writing-Review and Editing. All authors have read and agreed to the published version of the manuscript.

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

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Data availability statement

The data presented in this study are available on request from the corresponding author.

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