NUTRITIONAL EVALUATION OF THE LEAVES OF *SAMANEA SAMAN*, *TERMINALIA CATAPPA*, AND *BLIGHIA SAPIDA* AS AGROFORESTRY FODDER FOR SUSTAINABLE RUMINANT PRODUCTION IN GHANA

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ABSTRACT

The scarcity of feed during dry seasons challenges ruminant productivity, requiring exploration of underutilised fodder species. This study evaluates the nutritional value and fermentative characteristics of Samanea saman, Terminalia catappa, and Blighia sapida leaves, focusing on their proximate compositions, fibre fractions, mineral content, bioactive compounds, in vitro fermentation characteristics, and potential for reducing methane gas emissions. Nutritionally, S. saman had the highest ($p < 0.05$) dry matter content (96.60%) and crude protein (22.98%) compared to B. sapida (15.98%) and T. catappa (22.46%). Blighia sapida had the highest ($p < 0.05$) crude fibre (46.21%) and ash content (8.69%), while T. catappa had the highest ($p < 0.05$) nitrogen-free extract (46.57%) and metabolizable energy (221.49 MJ/g). In terms of minerals, S. saman had the highest ($p < 0.05$) phosphorus (0.72%), potassium (1.83%), and iron (220.35 mg/kg), while B. sapida had the highest ($p < 0.05$) calcium (1.62%) and magnesium (0.84%), and T. catappa had the highest ($p < 0.05$) copper (90.17 mg/kg). For bioactive compounds, T. catappa had the highest ($p < 0.05$) tannin, phytate, and oxalate levels, while B. sapida had the highest ($p < 0.05$) saponin content. At 96 hours of in vitro ruminal incubation, T. catappa exhibited the highest ($p < 0.05$) total gas production (15.00 ml/200g DM), followed by B. sapida (14.17 ml/200g DM) and S. saman (7.58 ml/200g DM). Blighia sapida and Terminalia catappa had higher insoluble fractions (12.39 -13.07 mL), while S. saman and T. catappa showed faster fermentation rates (0.10 - 0.11 mL/h). Terminalia catappa also produced the highest ($p < 0.05$) levels of lactic acid (13.02 mmol/100g), total volatile fatty acids (148.43 mmol/100g), butyric acid (9.54 mmol/100g), propionic acid (9.99 mmol/100g), methane gas (59.33%), and short-chain fatty acids (0.22 mol/100g). Samanea saman followed with moderate levels of volatile fatty acids and methane (54.59%), while B. sapida had the lowest values for lactic acid (6.45 mmol/100g), total volatile acids (73.54 mmol/100g), and methane gas (51.44%) ($p < 0.05$). However, B. sapida recorded the highest ($p < 0.05$) acetic acid (10.47 mmol/100g) and valeric acid (9.49 mmol/100g) levels, with the highest ruminal pH (7.49) among the fodder species. In conclusion, all the fodder plant species have demonstrated distinct nutritional and fermentative benefits that can enhance ruminant productivity during dry seasons. Further research should focus on their optimal inclusion rates and long-term impacts on ruminant health and productivity.

Keywords: *Fodders, chemical composition, ruminant, sustainable livestock management*

INTRODUCTION

Livestock production plays an indispensable role in the economies of many countries worldwide, particularly in developing nations, where it significantly contributes to rural livelihoods, food security, and poverty alleviation (Kaitibie et al., 2008). In Sub-Saharan Africa, where the economy is largely agrarian, livestock is essential for socio-economic stability, especially in regions characterized by arid and semi-arid climates (Timpong-Jones et al., 2023). Among the various livestock practices in these regions, transhumance pastoralism, where pastoralists move their herds seasonally between fixed grazing areas, holds particular importance for food security and rural livelihoods (Timpong-Jones et al., 2023). This practice is vital in developing countries, where livestock systems account for a significant portion of the national economy (Herrero et al., 2013). While the contribution of livestock to GDP may be less significant in countries like Ghana compared to more arid West African countries such as Mali and Niger, it remains a key livelihood source, particularly in rural areas (Chineke, 2022). Livestock also plays a multifaceted role beyond nutrition, contributing to cultural practices, manure production, and acting as a form of insurance against crop failure (Nwobodo et al., 2022).

The role of livestock in developing countries encompasses a wide range of production systems, from extensive pastoral systems, which occupy large areas with low human population densities, to mixed crop-livestock systems in areas suitable for both agriculture and livestock production (Herrero et al., 2013). Globally, the developing world accounts for a substantial share of livestock production, contributing 50% of beef, 59% of poultry, and 72% of lamb (Herrero et al., 2009). This highlights the importance of the livestock sector for global food security, particularly in sub-Saharan Africa. In many countries in the region, livestock production is a vital income source for rural households, providing direct and indirect employment in sectors such as meat, milk, egg, and fish production (Grace et al., 2008).

Despite its significance, livestock production in developing countries faces a multitude of challenges, particularly those related to feed scarcity, high feed costs, and environmental factors such as climate change (Meissner et al., 2013). The increasing urbanization and the need to balance agricultural land use for both cropping and livestock production further complicate the situation (Omore et al., 2001). Feed scarcity, especially during the dry seasons, is one of the most pressing challenges faced by livestock farmers in Sub-Saharan Africa (Anim, 2022). As the availability of traditional pasture grasses diminishes during these seasons, livestock experience nutrient deficiencies that hinder their productivity (Simbaya et al., 2020). This feed shortage not only affects the health and growth of the animals but also limits overall livestock productivity, thereby threatening food security in rural areas.

One of the core problems exacerbating feed scarcity in Sub-Saharan Africa is the lack of high-quality, seasonally available feed sources (Sasu et al., 2023a). During the dry season, traditional pasture grasses are insufficient, and their nutritional quality is often compromised (Simbaya et al., 2020). This creates a critical gap in livestock nutrition, which, if not addressed, could significantly reduce the sustainability of livestock production in the region. As a result, there is a growing recognition of the need for alternative feed resources that can address these seasonal feed gaps and provide ruminants with the necessary nutrients throughout the year.

In Ghana, agroforestry, particularly the use of underutilized fodder plants, offers a promising solution to these challenges. Agroforestry fodder plants are particularly advantageous due to their resilience to seasonal variations and their ability to provide consistent feed availability during dry periods. Furthermore, these plants often have superior nutritional profiles compared to traditional pasture grasses, making them valuable additions to ruminant diets (Sasu et al. 2023b). Among the potential candidates for agroforestry fodder in developing countries, *Samanea saman*, *Blighia sapida*, and *Terminalia catappa* stand out for their ability to thrive in tropical climates and their promising nutritional benefits for livestock (Yusuf et al., 2020). These plants, which are often underutilized in many regions, may possess nutritional qualities that could support ruminant production by bridging the feed gap during dry seasons (Simbaya et al., 2020).

Samanea saman, commonly known as the Rain Tree or Monkey Pod, is a drought-resistant tree that retains abundant foliage even during the dry season, making it an excellent candidate for providing sustainable fodder in tropical climates (Yusuf et al., 2020). Similarly, *Blighia sapida*, also known as the Akee tree, is evergreen and continues to offer fodder even when other sources of forage are scarce (Sasu et al. 2023b). *Terminalia catappa*, the Indian almond or Tropical almond, is another tree that is cultivated in tropical areas, often near coastlines, and has nutrient-rich leaves that can be utilized as fodder (Simbaya et al., 2020). These trees are known for their resilience to adverse climatic conditions and their ability to provide consistent, high-quality feed for livestock, particularly in areas where conventional feed resources are limited.

In the context of ruminant nutrition, the potential benefits of these agroforestry fodder plants go beyond merely providing feed during periods of scarcity. Their consistent availability can help reduce the dependence on conventional pasturelands, alleviate pressure on natural resources, and contribute to more sustainable livestock production systems (Godde et al., 2021). By integrating these plants into ruminant diets, farmers can lower feed costs, increase livestock productivity, and improve the resilience of their herds to climate-related challenges. Moreover, the use of these plants may contribute to mitigating the environmental impact of livestock production, including reducing greenhouse gas emissions, a significant concern in the livestock sector. This study evaluated the nutritional potential of *S. saman, B. sapida,* and *T. catappa* leaves as an alternative feed for ruminants in Ghana, focusing on their proximate composition, mineral content, fibre fractions, bioactive compounds, and *in vitro* fermentation characteristics, including gas production and methane emissions. The aim was to assess their feasibility as sustainable feed options that could enhance livestock farming and food security in Ghana and Sub-Saharan Africa.

MATERIALS AND METHODS

Ethical clearance

The Animal Research Ethics Committee (AREC) of the Quality Assurance and Planning Unit of the Kwame Nkrumah University of Science and Technology, Kumasi, provided the appropriate standard operating procedures, all of which were followed.

Location of the study

The analytical chemical composition and *in vitro* gas production were carried out in the Department of Animal Science, Faculty of Agricultural Science, Kwame Nkrumah University of Science and Technology (KNUST). The mineral composition was determined at the Department of Soil Science, Faculty of Agricultural Science, Kwame Nkrumah University of Science and Technology. The phytochemical analysis, methane, and volatile fatty acids analyses were carried out at the Department of Animal Science, University of Ibadan, Oyo State Nigeria.

Leaf sample collection and preparation

Fresh leaves of *T. catappa, B. sapida*, and *S. saman* were collected from the KNUST botanical garden during the rainy season on 15th March 2023. Five plants of each species were considered for sampling from three different locations within the earmarked zone. Two distinct plant branches on each plant species that were not noticeably over-matured were cut. After cutting, the leaves and twigs were plucked out from the branches and bulked together into separate containers. A representative triplicate samples from each bulked sample were prepared to get the statistical repetitions. The samples were chopped into smaller pieces using an electric grinder, air-dried at room temperature for 24 hours, and subsequently dried in an oven at 60–65°C for 24 hours to achieve a constant weight, ensuring minimal denaturation of proteins. The oven-dried samples were coarsely milled individually using a laboratory mill (Wiley Mill[1]) to pass through a 0.2 mm screen and then placed in Ziploc bags for further chemical and nutritional analyses.

Proximate Analysis

The proximate analytical procedure was employed by following the standard procedures of the Association of Official Analytical Chemists (AOAC, 2016) to determine dry matter (DM), crude protein (CP = N * 6.25), ether extract (EE), crude fibre (CF), ash and nitrogen-free extract (NFE).

Detergent Fibre Analysis

The ANKOM 2000 Automated Fiber Analyzer[2] was used to determine the contents of neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) using standard procedures (Van Soest *et al.*, 1991). The cellulose (CEL), hemicellulose (HEM), metabolizable energy (ME), and short-chain fatty acid (SCFA) contents were calculated using the following formula:

$$\%\ \text{Cellulose} = \%\ \text{ADF} - \%\text{ADL} \qquad \text{----}\ (1)$$

$$\%\ \text{Hemicellulose} = \%NDF - \%ADF \qquad \text{----}\ (2)$$

Mineral Analysis

The samples were analysed for iron (Fe), copper (Cu), manganese (Mn), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) according to the methods described by Motsa et al. (2005) and Lee and Campbell (1969).

Phytochemical Analysis

The phytochemical analysis included both qualitative and quantitative evaluations. For qualitative screening, seven bioactive compounds were identified: tannins, saponins, glycosides, flavonoids, alkaloids, triterpenoids, and phytosteroids. Quantitative analysis measured six specific compounds: tannins, saponins, oxalates, phenolics, flavonoids, and total antioxidants. These assessments were performed using milled leaf samples, following the methodologies described by Chapman (1980), Banerjee (1957) and Lolas and Markakis (1975).

In Vitro Degradation and Gas Production

The rumen fluid used for in vitro degradability and gas emission studies was collected from four male N'dama beef cattle, approximately three and a half years old, with an average live weight of 277 kg. These animals were slaughtered at the Kumasi Abattoir Company Limited in Ghana. As soon as the carcasses were opened, the rumen digesta was collected, put in a pre-warmed vacuum flask and transported to the lab. The digesta was then strained through a four-layered cheesecloth while carbon dioxide was continuously flushed out to preserve anaerobic conditions to obtain the rumen liquor. A buffer was mixed with the rumen liquor in a ratio of one part liquor to four parts buffers. Using the standard procedure, 200 milligrams of the plant samples were cultured in a rumen liquor-buffer mixture within a glass syringe that had been calibrated. Three separate runs of incubation were conducted at 39◦C in a water bath. To get nine statistical repetitions, each run involved incubating triplicates of each sample and measuring the quantities of gas produced after 3, 6, 12, 24, 48, 76, and 96 hours. Three blank glass syringes containing only rumen liquor and buffer were included in each run. Gas readings were analysed using SigmaPlot (Version 15.0, Systat Software Inc., 2017) and fitted to the following model:

$$Y = b\left(1 - e^{ct}\right) \qquad \text{----}\ (3)$$

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[1] *The Thomas ® Model 4 Wiley Mill. Made in the USA. Marketed and distributed by Onrion LLC. 93 South Railroad Avenue, STE C Bergenfield, 07621-2352, New Jersey, USA.*

[2] *The ANKOM 2000 Automated Fiber Analyzer. Made in USA. Marketed anddistributed by ANKOM Technology, Macedon NY 14502, 2052 O'Neil Road.*

Where

Y = the potential gas production (ml),
b = potential gas production (ml/200 mg DM),
t = incubation time and,
c = the fractional rate of gas production (ml/hr)

Short-chain fatty acids (SCFA) and metabolisable energy were predicted according to the equations of Menke and Steingass (1988) using the following formula:

$$SCFA = [-0.00425 + 0.0222 \times IVG\ 24] \quad \text{---- (4)}$$

$$\mathrm{ME} = \left(\frac{\mathrm{M}}{\mathrm{KGDM}}\right) = 2.20 + (0.0316 \times \mathrm{GP24}) + (0.057 \times \mathrm{CP}) \quad \text{---- (5)}$$

Where GP_{24} = 24 h gas volume (ml/200 mg), CP = crude protein (%DM) and ash (%DM) of the incubated samples, respectively.

To measure methane and carbon dioxide, 2 g of dried sample was gasified using the aerobic combustion technique. A gas regulator trapped 30 cm^3 of gas in a Pascal manometric glass tube, which had been pre-filled with a known volume of fractionating reagent mixture comprising 1M magnesium perchlorate, 1M sodium hydroxide, 1M barium sulfate, and 1M nitric acid. Fractionation of gases was based on the redox principle, wherein reduction-oxidation reactions precipitated specific gas fractions. The percentage of methane and carbon dioxide in the gas was calculated using Equation 6. Rumen liquor was strained through a muslin cloth into a 250 ml beaker, followed by the addition of 25 ml of saturated 1M H_2SO4. The mixture was thoroughly stirred, allowed to stand for 10 minutes, and subsequently filtered through Whatman No. 12 filter paper into a 100 ml volumetric flask. A 2 ml aliquot of the filtrate was pipetted into the Markham Distillation Apparatus via its funnel aperture and distilled into a 100 ml conical flask until 30 ml of distillate was collected. This distillation was repeated four times for each sample. To remove dissolved CO_2, nitrogen gas was bubbled through each distillate. The distillates were titrated against 0.01M NaOH using bromothymol blue as an indicator. The total volatile fatty acids (TVFA) concentration was calculated using Equation 7. For the fractionation of volatile fatty acids (acetic, propionic, butyric, and valeric acids), Equation 8 was used. The total absorbance for gas fractions, including CO_2 and other volatile gases, was determined using Equation 9. The absorbance readings for each VFA fraction and gas sample were measured using a spectrophotometer to ensure precise determination.

Methane, Carbondioxide (%)

$$= \frac{a \times 76.08}{\text{The volume of gas used}} \quad \text{----- (6)}$$

$$\mathrm{TVFA}\left(\frac{\mathrm{mmol}}{100}ml\right)$$

$$\text{VFA fractions } \left(\frac{\mathrm{mmol}}{100\mathrm{ml}}\right)$$

= Absorbance of sample x Gradient factor x Dilution factor ---(8)

Gas fraction (%)

$$= \frac{\text{The absorbance value of the sample}}{\text{The absorbance of the standard gas}} \times 100 \quad \text{--- (9)}$$

Statistical Analysis

All data were arranged in a Completely Randomized Design and were analyzed using the GLM procedure of Minitab Statistical Software, version 19.0 (Minitab, LLC, NY, US, 2019). The plant type served as the experimental units. The chemical compositions (DM, OM, CP, CF, EE, NFE, ash, NDF, ADF, ADL, CEL, and HEM), minerals (Ca, K, P, Mg, Fe, Cu) and phytochemical components (tannins, saponins, oxalates and phytates) were considered as the response (variables) whilst the plant species evaluated were considered as the factors (fixed term). For methane gas, the plants stand as an experimental unit while gas percentage represents the response variable. The volatile fatty acid composition for each plant species represents the variable while the plant species stands as the experimental unit. All comparisons between means were tested using the Tukey method at a $p < 0.05$ significance level of acceptance.

RESULTS

Analytical Proximate *Composition of the Fodder Species*

Table 1 shows the results of the analytical chemical composition of the fodder species.

A notable variation ($p < 0.05$) in their nutritional constituents emerged. Dry matter content was highest in *S. saman* (96.60%), followed by *B. sapida* (89.37%), and *T. catappa* (87.99%). Crude protein content revealed *S. saman* (22.98%) and *T. catappa* (22.46%) to be statistically similar, with *B. sapida* (15.98%) showing a significantly lower value. The highest crude fibre content (46.21%) was recorded for *B. sapida*, significantly exceeding *S. saman* (24.98%) and *T. catappa* (20.74%). Regarding ash content, *B. sapida* (8.69%) again exceeded *S. saman* (3.283%) and *T. catappa* (6.80%). There were no significant differences ($p < 0.05$) in ether extract and nitrogen-free extract contents while *S. saman* exhibited a slightly higher ($p < 0.05$) metabolizable energy value (222.15 MJ/g) compared to both *B. sapida* (221.99 MJ/g) and *T. catappa* (221.49 MJ/g).

Analytical Detergent Fibre *Composition of the Fodder Species*

Table 2 shows the results of the detergent fibre fractions. Significant variations in several parameters were observed. Neutral detergent fibre (NDF) content was significantly lower in *T. catappa* (44.433%) and *S. saman* (47.207%) compared to *B. sapida* (63.284%) ($p < 0.05$). A similar trend was observed in acid detergent fibre (ADF) with *S. saman* and *T. catappa* having lower values than *B. sapida* (56.182%). However, Acid detergent lignin (ADL), cellulose and hemicellulose contents exhibited no significant differences ($p > 0.05$) among the leaf samples.

Analytical Detergent Fibre *Composition of the Fodder Species*

Table 3 shows the results of the bioactive components of the fodder species. Tannin, phytate and oxalate levels varied among the three leaf samples ($p < 0.05$), with *T. catappa* having the highest levels of the contents while *B. sapida* had the least Saponins detected in all three leaf samples, with *B. sapida* having the highest levels (0.28%) while *T. catappa* had the least (0.24%) ($p < 0.05$).

Table 1: Analytical chemical composition of the three leaf samples

Parameters (%)	Fodder Species			SEM	P-value
	S. saman	*B. sapida*	*T. catappa*		
Dry Matter	96.60^a	89.37^b	87.99^b	0.646	0.0002
Crude Protein	22.98^a	15.98^b	22.46^a	0.136	0.0001
Ether Extract	3.56	1.62	3.43	0.661	0.1463
Crude Fibre	24.98^b	46.21^a	20.74^b	5.458	0.0341
Ash	3.28^c	8.69^a	6.80^b	0.218	0.0001
Nitrogen-free extract (NFE)	45.19	27.50	46.57	5.768	0.1030
Metabolizable Energy (ME) (MJ/g)	222.15^a	221.99^a	221.49^b	0.076	0.0020

Mean values on the same row with different superscripts (a, b, c) are significantly (p <0.05) different.
SEM =standard error of means

Table 2: Analytical detergent fibre fractions of the leaf samples

Parameters (%)	Fodder Species *S. saman*	*B. sapida*	*T. catappa*	SEM	p-value
Neutral detergent fibre (NDF)	47.21^b	63.28^a	44.43^b	2.155	0.0017
Acid detergent fibre (ADF)	35.72^b	56.18^a	39.18^b	1.639	0.0002
Acid detergent lignin (ADL)	11.57	46.51	46.32	13.60	0.1930
Cellulose	24.15	9.68	7.15	13.00	0.3080
Hemicellulose	11.49	7.10	5.26	2.350	0.2370

Mean values on the same row with different superscripts (a, b, c) are significantly (p <0.05) different.
SEM = standard error of means

Table 3: Analytical phytochemical constituents of the leaf samples

Parameters (%)	Fodder Species *S. saman*	*B. sapida*	*T. catappa*	SEM	p-value
Tannins	0.002^b	0.001^c	0.003^a	0.0001	0.0001
Phytate	0.015^b	0.140^c	0.017^a	0.0002	0.0001
Oxalate	0.013^b	0.012^c	0.015^a	0.0002	0.0001
Saponins	0.260^b	0.280^a	0.240^c	0.0020	0.0001

Mean values on the same row without superscripts (a, b, c) are significantly (p <0.05) different.
SEM =standard error of means

Analytical Mineral *Composition of the Fodder Species*

Table 4 shows the results of the mineral composition. Phosphorus (P) content varied significantly among the three forages, with *S. saman* (0.72%) having the highest level, followed by *B. sapida* (0.51%), and *T. catappa* (0.48%) ($p < 0.05$). Calcium (Ca) content displayed a similar trend, with *S. saman* (1.30%) being significantly lower than *B. sapida* (1.62%) and *T. catappa* (1.36%). Potassium (K) content was highest in *S. saman* (1.83%), followed by *B. sapida* (1.32%) and *T. catappa* (1.09%) ($p < 0.05$). Magnesium (Mg) content was significantly higher in *B. sapida* (0.84%) compared to both *S. saman* (0.40%) and *T. catappa* (0.75%) ($p < 0.05$). In terms of trace minerals, Iron (Fe) was highest in *S. saman* (220.35 mg/kg), followed by *T. catappa* (214.13 mg/kg) and *B. sapida* (179.90 mg/kg), while Copper (Cu) was highest in *T. catappa* (90.17 mg/kg), followed by *S. saman* (68.86 mg/kg) and *B. sapida* (48.40 mg/kg) ($p < 0.05$).

In vitro Fermentation Profile and Emission Reduction Potential of the Fodder Species

Table 5 illustrates the *in vitro* gas production (IVGP) profile and greenhouse gas emission reduction capacity of the fodder species. From the table, a clear progression in gas production was observed with increasing incubation time. Notably, at the 3-hour incubation period, *S. saman* exhibited significantly lower gas production (2.0 mL) compared to *B. sapida* (4.5 mL) and *T. catappa* (6.17 mL) ($p < 0.05$), a trend that persisted across the multiple time intervals up to the 96-h of incubation. This gas production pattern followed the sequence *T. catappa* > *B. sapida* > *S. saman* as depicted in Figure 1.

In the context of degradation kinetics, there were notable variations in the insoluble fractions (b) of gas produced, with *T. catappa* exhibiting the highest value (13.07 mL), followed by *B. sapida* (12.39 mL), surpassing *S. saman* (7.58 mL) ($p < 0.05$). However, *S. saman* and *T. catappa* showed faster fermentation rates (0.10 and 0.11 mL/h), while *B. sapida* had a slower rate (0.08 mL/h) ($p < 0.05$).

This pattern contrasted with the constant rate for insoluble fractions (c), where *T. catappa* (0.11 mL/h) and *S. saman* (0.10 mL/h) displayed similar values that differed from *B. sapida* (0.08 mL/h).

Table 4: Analytical mineral composition of the leaf samples

Parameters (%)	**Fodder Species**			**SEM**	**P-value**
	S. saman	***B. sapida***	***T. catappa***		
Phosphorus (P)	0.72^{a}	0.51^{b}	0.48^{c}	0.0069	0.0001
Calcium (Ca)	1.30^{c}	1.62^{a}	1.36^{b}	0.0098	0.0001
Potassium (K)	1.83^{a}	1.32^{b}	1.09^{c}	0.0285	0.0001
Magnesium (Mg)	0.40^{c}	0.84^{a}	0.75^{b}	0.0066	0.0001
Iron (Fe)(mg/kg)	220.35^{a}	179.90^{b}	214.13^{a}	3.6535	0.0001
Copper (Cu)(mg/kg)	68.86^{b}	48.40^{c}	90.17^{a}	0.8214	0.0001

Mean values on the same row with different superscripts (a, b, c) are significantly ($p < 0.05$) different.
SEM =standard error of means

Table 5: *In vitro* gas production and degradation kinetics of the forage leaves

Incubation time (hr)	***Gas Production, ml/200gDM***			**SEM**	**p-value**
	S. saman	***B. sapida***	***T. catappa***		
3	2.0^{b}	4.5^{ab}	6.17^{a}	0.977	0.003
6	3.67^{b}	6.00^{ab}	7.50^{a}	1.010	0.004
9	4.50^{b}	6.83^{ab}	8.33^{a}	0.631	0.000
12	5.17^{b}	7.00^{ab}	8.67^{a}	0.674	0.275
24	5.67^{b}	9.00^{a}	10.00^{a}	0.585	0.316
36	7.50^{b}	10.00^{ab}	11.67^{a}	0.518	0.101
48	7.83^{b}	11.50^{a}	13.00^{a}	0.544	0.204
72	7.50^{b}	13.17^{a}	14.17^{a}	1.770	0.301
96	7.58^{b}	14.17^{a}	15.00^{a}	0.585	0.166
			Degradation Kinetics		
Insoluble fractions (b) (mL)	7.50^{b}	12.39^{a}	13.07^{a}	0.772	0.011
Rate of fermentation (c) mL/h)	0.10^{a}	0.08^{b}	0.11^{a}	0.050	0.001

Mean values on the same row with different superscripts (a, b, c) are significantly ($p < 0.05$) different.
SEM =standard error of means

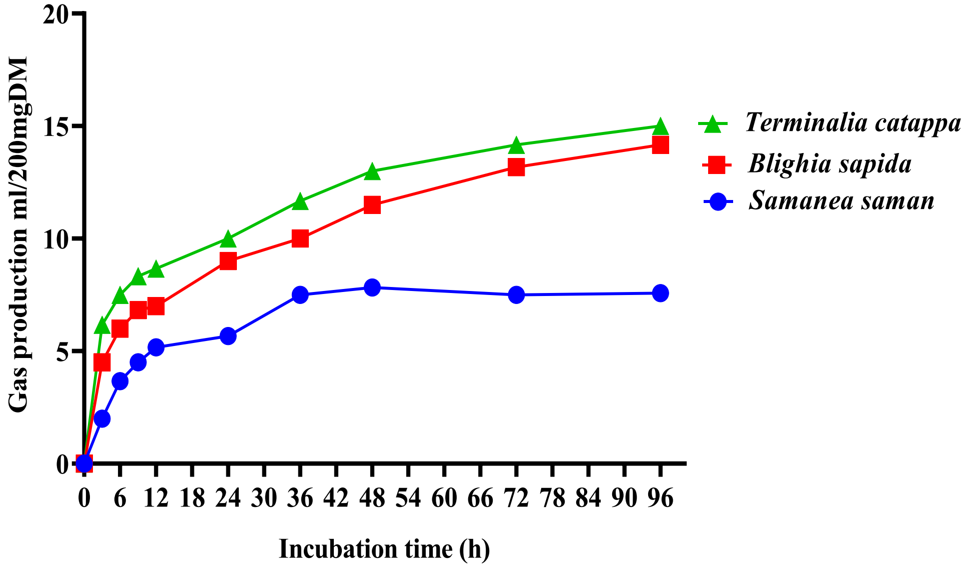

Figure 1: ***In vitro*** **gas production pattern of the incubated leaf samples**

Table 6: Volatile fatty acids (VFA) and methane (CH_4) content of the leaves

Parameter	**Fodder Species**			**SEM**	**p-value**
	S. saman	***B. sapida***	***T. catappa***		
Lactic acid (mmol/100g)	12.11^b	6.45^c	13.02^a	0.097	0.001
Total volatile acid mmol/100g)	137.97^b	73.54^c	148.43^a	0.071	0.001
Acetic acid (mmol/100g)	9.73^b	10.47^a	5.19^c	0.977	0.001
Butyric acid (mmol/100g)	8.87^b	4.73^c	9.54^a	0.075	0.001
Propionic acid (mmol/100g)	9.28^b	4.95^c	9.99^a	0.078	0.001
Valeric acid (mmol/100g)	8.82^b	9.49^a	4.70^c	0.793	0.001
Short-chain fatty acid mol/100g)	0.12^b	0.20^a	0.22^a	0.005	0.130
Methane gas (%)	54.59^b	51.44^c	59.33^a	0.593	0.001
NH_3-N (mmol/100g)	184.64^a	143.61^c	155.40^b	1.630	0.001
pH	5.66^c	7.49^a	6.31^b	0.012	0.001

Mean values on the same row with different superscripts (a, b, c) are significantly ($p < 0.05$) different.
SEM =standard error of means

In the assessment of volatile fatty acids (VFA), carbon dioxide (CO_2) and methane (CH4) content in the fodder species, notable differences emerged in several parameters. Lactic acid content (mmol/100g) was significantly higher in *T. catappa* (13.02) and *S. saman* (12.11) compared to *B. sapida* (6.45) ($p < 0.05$), with a similar trend observed for total volatile acid content (mmol/100g), where *T. catappa* (148.43) and *S. saman* (137.97) exceeded *B. sapida* (73.54). Acetic acid (mmol/100g) was highest in *B. sapida* (10.47), followed by *S. saman* (9.73) and *T. catappa* (5.19), whereas butyric acid (mmol/100g) was significantly higher in *S. saman* (8.87) and *T. catappa* (9.54) compared to *B. sapida* (4.73) ($p < 0.05$). Propionic acid (mmol/100g) and valeric acid (mmol/100g) exhibited similar trends, with higher values in *S. saman* and *T. catappa* compared to *B. sapida*. However, there were no significant differences in short-chain fatty acid content (mmol/100g) ($p > 0.05$).

Carbon dioxide and methane gas production (%) were significantly higher in *T. catappa* (59.33) and *S. saman* (54.59) than in *B. sapida* (51.44) ($p < 0.05$). The concentration of NH3-N (mmol/100g) was highest in *S. saman* (184.64), followed by *T. catappa* (155.40) and *B. sapida* (143.613). Lastly, pH levels indicated significantly higher alkalinity in *B. sapida* (7.49), while *S. saman* (5.66) and *T. catappa* (6.31) exhibited lower values ($p < 0.05$).

DISCUSSION

The nutritional evaluation of Samanea saman, Blighia sapida, and Terminalia catappa underscores their potential as valuable feed resources for ruminants in tropical regions. These species exhibit diverse nutritional and bioactive compositions, which not only enhance livestock productivity but may also contribute to environmental sustainability by mitigating greenhouse gas emissions. Improved feed efficiency, stemming from better digestibility and nutrient availability, is a key mechanism through which these species could reduce methane emissions in ruminant systems. This aligns with global sustainability goals, particularly in the context of tropical livestock production where feed resources are often limited by seasonal availability and variable quality.

The dry matter (DM) content of these species, a critical factor in determining feed quality and nutrient availability, varied significantly in this study, offering insight into their utility for ruminant feeding. The DM content of S. saman, for instance, exceeded values reported in previous studies, such as 46.12% by Sariri and Kustantinah (2022) and 34.19% by Ojeda et al. (2012). This disparity could be attributed to differences in plant maturity, climatic conditions, or drying methods. As noted by Delgado et al., 2024, mature plants tend to accumulate more structural carbohydrates, which can lead to elevated DM levels. Additionally, drying techniques, such as oven-drying versus air-drying, can influence moisture retention and, consequently, the DM content (Ojeda et al., 2012). The high DM content of *S. saman* observed in this study is particularly advantageous for storage and preservation, as it minimises the risk of microbial spoilage while ensuring nutrient retention over extended periods. This is consistent with the findings of Animal et al. (2014), who highlighted the importance of high DM for maintaining feed quality during storage. Such attributes make *S. saman* a reliable feed resource, especially in tropical regions where seasonal variations in forage availability necessitate feed conservation strategies. Moreover, the relatively moderate fibre content of *S. saman* compared to other browse species further enhances its digestibility and overall suitability for ruminant diets. In comparison, the DM values of *B. sapida* and *T. catappa* were consistent with findings from Sarkwa et al. (2021) and Omosowone and Adebayo (2022), respectively. However, *B. sapida* exhibited slightly lower DM content than the 96% reported by Aderinola et al. (2007) and Osman et al. (2020). These discrepancies may result from environmental factors, such as soil type and rainfall patterns, as well as variations in sample preparation. For instance, forage samples harvested during the rainy season may retain higher moisture levels, thereby reducing their DM content (Ojeda et al., 2012). While the high DM content observed in these species is beneficial for nutrient provision and storage, exceptionally high DM levels, as reported in some studies on *B. sapida*, may reduce palatability, potentially limiting feed intake by ruminants. According to Mertens (1994), excessively dry feed can hinder voluntary intake, especially in tropical livestock that may already face challenges related to heat stress and water scarcity. Thus, achieving a balance between DM content and palatability is crucial for optimising the utilisation of these fodder species in ruminant diets. In contrast, the DM content of *T. catappa* was more moderate, aligning closely with the values reported by Omosowone and Adebayo (2022) but surpassing those documented by Amata and Lebari (2011). This indicates that *T. catappa* could serve as a versatile feed resource with consistent nutrient availability.

Crude protein is essential for optimal growth, reproduction, and immune function in ruminants. The CP content of *S. saman* in this study exceeded values reported for mature leaves by Ojeda et al. (2012) and Animal et al. (2014) but was lower than CP levels in young leaves as noted by Animal et al. (2014). This reinforces the observation that plant age significantly influences CP levels, with younger leaves generally being more nutrient-dense. Crude protein (CP) plays a pivotal role in supporting optimal growth, reproduction, and immune function in ruminants, making it a critical parameter for evaluating feed resources. The CP content of *S. saman* observed in this study exceeded values reported for mature leaves by Ojeda et al. (2012). However, it was lower than the levels documented in young leaves by Animal et al. (2014), reaffirming the well-established influence of plant maturity on CP levels. Younger leaves are generally more nutrient-dense due to their higher concentrations of proteins and other essential nutrients during active growth stages, which decline as the plant matures. The CP content of *B. sapida* and *T. catappa* also compared favourably with values reported by Aderinola et al. (2007), Osman et al. (2020) and Omosowone and Adebayo (2022), highlighting its consistent nutrient profile and suitability for ruminant diets.

Ether extract (EE) content is a vital indicator of the energy value of feed, providing essential fatty acids and contributing to the overall energy density of ruminant diets. Among the species studied, *T. catappa* exhibited relatively high EE levels. However, these were lower than the values reported by Omosowone and Adebayo (2022) and Offor et al. (2015). Similarly, the EE content in *S. saman* aligned with the findings by Ojeda et al. (2012) and Animal et al. (2014) but exceeded the values reported by Datt et al. (2008). These discrepancies across studies may be attributed to factors such as plant maturity, soil type, and post-harvest processing methods. For instance, younger plants tend to accumulate more soluble lipids, while soil fertility and drying techniques can further influence lipid retention. The moderate EE levels observed across all three species are noteworthy. While EE contributes significantly to the energy density of diets, excessive dietary fat can impair rumen fermentation, reduce fibre digestibility, and ultimately affect animal performance (Forbes, 2007). Therefore, the moderate EE content in *S. saman*, *T. catappa*, and *B. sapida* aligns with recommendations for safe inclusion levels in ruminant diets. This balance ensures adequate energy provision without compromising rumen function, making these species suitable for tropical livestock systems. Notably, the high EE content in *T. catappa* positions it as an excellent energy source among the three species, potentially enhancing energy availability in rations where traditional forages fall short. However, the EE content in *S. saman* and *B. sapida* also could provide sufficient energy to meet the demands of moderate-production ruminants. This versatility allows for the strategic incorporation of these species into ruminant feeding programmes to optimise energy intake while preventing the adverse effects of excessive dietary fat.

Fibre plays a critical role in maintaining rumen function and optimising digestibility, yet its effects can vary depending on concentration and composition. Among the species studied, *B. sapida* exhibited the highest crude fibre (CF) content, surpassing values reported by Aderinola et al. (2007) and Osman et al. (2020). In contrast, the CF content of *S. saman* was moderate and aligned with the findings of Sariri and Kustantinah (2022). High fibre levels, although essential for rumen health, can compromise digestibility and reduce voluntary feed intake, as highlighted by Maneesh et al. (2015). When compared to recommended thresholds for ruminant feeds, less than 31% for acid detergent fibre (ADF) and approximately 40% for neutral detergent fibre (NDF), the elevated fibre levels in all three species suggest they should be used judiciously in rations. Excessive fibre can slow the rate of passage and limit energy availability, underscoring the importance of balancing these fibre-rich forages with low-fibre supplements. This approach ensures rumen health is supported without compromising nutrient intake or overall productivity. The moderate fibre content of *S. saman* positions it as a versatile feed resource, particularly when combined with concentrates to enhance digestibility. Meanwhile, the high fibre levels in *B. sapida* may be better suited for use in maintenance diets or as part of total mixed rations to meet structural fibre requirements.

Ash content, an indicator of a feed's mineral composition, is crucial for supporting various physiological functions, including enzymatic activity and skeletal development. The ash content observed in all three species was consistent with findings by Sasu et al. (2023b), indicating their potential as sources of essential minerals. Moreover, their mineral profiles resembled those of subtropical pastures, as reported by Lowe et al. (2016). However, deficiencies in key minerals such as iron, copper, magnesium, potassium, and calcium were noted. These deficiencies highlight the importance of strategic mineral supplementation when these fodders are used as primary feed resources. Balancing these species with mineral-rich supplements or fortified concentrates can address these gaps and enhance their nutritional value. For instance, calcium deficiencies could be offset with limestone supplementation, while magnesium-rich mineral blocks can improve overall mineral balance.

The presence of bioactive compounds such as tannins and oxalates across all the fodder species analysed underscores their potential antioxidant capacity. These compounds are known to scavenge free radicals, thereby reducing oxidative stress and contributing to improved animal health and productivity (Pathak et al., 2017). The antioxidant properties of tannins, in particular, have been associated with enhanced immune response and better overall physiological performance in ruminants. However, the effects of these bioactive compounds on ruminants are dose-dependent. While moderate levels of tannins can improve protein utilisation by protecting dietary proteins from rumen degradation, excessive levels may reduce palatability and interfere with nutrient absorption (Mahachi et al., 2020). Similarly, oxalates, though beneficial in small amounts due to their mineral-binding capacity, can pose risks of calcium deficiency or kidney damage when consumed in high quantities (Manzoor et al., 2021). The balanced concentrations of these bioactive compounds observed in *S. saman*, *B. sapida*, and *T. catappa* suggest they have significant nutritional and health-promoting potential for ruminants. By acting as natural antioxidants, these compounds contribute to feed quality and support the resilience of livestock against oxidative stress. Furthermore, their inclusion in ruminant diets aligns with sustainable livestock management practices by reducing reliance on synthetic antioxidants. Nonetheless, the practical application of these fodder species in diets requires careful management to avoid potential antinutritional effects. Strategies such as proper processing, ensiling, or supplementation with mineral-rich feed additives can mitigate the adverse effects of higher tannin or oxalate concentrations while preserving their antioxidant benefits.

The chemical composition and bioactive properties of the fodder species analysed significantly influenced their ruminal fermentation characteristics and greenhouse gas emission potential. The relationship between tannins, saponins, fibre, and fermentation variables provides insight into their mechanisms in reducing greenhouse gas emissions, particularly methane (CH_4). Despite *T. catappa* exhibiting the highest tannin content, it paradoxically produced the highest methane (CH_4) emissions. This finding contradicts the widely accepted notion that tannins suppress methane production by inhibiting methanogenic archaea or reducing hydrogen availability in the rumen (Hess et al., 2006; Goel and Makkar, 2012). However, the high fermentable substrate in *T. catappa* may have overridden the inhibitory effects of tannins by providing abundant organic matter for microbial degradation. Typically, tannins reduce methane emissions by binding to dietary proteins and carbohydrates, thereby limiting substrate availability for methanogenesis. The observed deviation in *T. catappa* suggests that the overall fermentation dynamics, influenced by fibre and substrate composition, may offset the direct effects of tannins on methane suppression. The saponin content in *S. saman* and *B. sapida* appeared to contribute to their reduced methane emissions. Saponins are known to disrupt rumen protozoal populations, indirectly limiting methanogen activity and reducing methane production (Kozłowska et al., 2020; Jayanegara et al., 2014). Additionally, saponins can shift fermentation towards reductive acetogenesis, promoting the formation of acetate rather than methane, as noted by Kumar et al. (2019). The reduced methane production in *S. saman* and *B. sapida* aligns with the findings of Sidhu and Wadhwa (2019), who highlighted the role of saponins in modifying ruminal microbial ecology and fermentation pathways. These results indicate that saponin-rich fodders offer potential as natural feed additives to mitigate greenhouse gas emissions. Fibre content significantly influences the fermentation process and greenhouse gas production. The low acid detergent fibre (ADF) content in *S. saman* likely facilitated rapid microbial fermentation, leading to lower gas production. Conversely, the high ADF and acid detergent lignin (ADL) content in *B. sapida* may have hindered microbial degradation, reducing methane and total gas production (Sasu et al., 2023b). Elevated lignin levels impede fibre digestibility by creating a physical barrier to microbial enzymes. This phenomenon explains the reduced gas production in *B. sapida* despite its moderate levels of fermentable substrates. The balance between fibre degradability and microbial activity determines the extent of fermentation and the associated methane emissions. Volatile fatty acids (VFAs) are critical indicators of ruminal fermentation efficiency. The total VFA concentrations observed in the fodder species fell within the optimal ranges (70–150 mmol/L) reported by Dhia et al. (2019) and Samadi et al. (2020), supporting effective microbial fermentation. The highest VFA concentrations in *T. catappa* correlated with its high fermentable substrate content, reflecting enhanced carbohydrate degradation. The high propionic acid levels in *T. catappa* suggest a shift in fermentation towards propionate production, reducing hydrogen availability for methane synthesis (Tseten et al., 2022). This shift enhances the energy efficiency of the rumen, as propionate serves as a glucogenic precursor absorbed directly into the bloodstream. In contrast, the lower VFA production in *B. sapida* may be attributed to its high saponin content, which suppresses microbial activity and fermentation rates (Sidhu and Wadhwa, 2019). These findings underscore the role of fodder composition in modulating fermentation end-products and greenhouse gas emissions. Ammonia nitrogen levels provide insight into protein degradation and utilisation in the rumen. The high NH_3-N concentrations in *S. saman* reflect its elevated crude protein content, supporting rapid protein digestion (Pratama et al., 2022). However, excessive NH_3-N can indicate an imbalance between protein degradation and microbial protein synthesis, leading to nitrogen losses through volatilisation.

Balancing crude protein levels with energy sources is essential to optimise NH_3-N utilisation and reduce nitrogen excretion into the environment. The differential methane emissions observed among the fodder species highlight their potential role in climate change mitigation. While fats in *B. sapida* reduced methane production by inhibiting protozoa and methanogens (and Hartutik, 2021), the combination of tannins and saponins in *S. saman* and *B. sapida* further contributed to methane suppression. The reduced methane emissions in *S. saman* and *B. sapida* align with strategies to enhance ruminal fermentation efficiency while minimising environmental impact. These results demonstrate the potential of integrating bioactive compound-rich fodders into ruminant diets to achieve sustainable livestock production.

CONCLUSION

This study highlights the potential of *Samanea saman, Blighia sapida,* and *Terminalia catappa* as sustainable livestock feed options, each with distinct benefits and challenges. *Samanea saman*, with its high protein content and digestibility, offers a valuable solution for improving livestock productivity, particularly in resource-limited settings. *Blighia sapida* provides a reliable source of fibre during dry periods, while its saponin content effectively reduces methane emissions. In contrast, *T. catappa*, despite its high fermentable substrate content, produced more methane, raising concerns about its environmental impact when used extensively. The findings reveal that bioactive compounds such as saponins and tannins play a significant role in influencing methane emissions and nutrient utilisation, with saponins showing greater potential for reducing greenhouse gases. These results emphasise the importance of balancing fodder inclusion levels, processing to reduce antinutritional factors, and considering dietary supplementation. By adopting these strategies, farmers can improve livestock productivity while contributing to global efforts to reduce greenhouse gas emissions and promote sustainable agriculture.

Research gap

There is a need to move beyond laboratory analyses to practical applications of these fodder species in livestock systems. Future studies should focus on their on-farm integration, cost-effectiveness, and long-term impact on livestock health and methane reduction. Research should also explore their adaptability to climate variability and species-specific responses to optimise feeding strategies. Developing clear, practical guidelines for farmers and assessing their environmental impact, including methane mitigation and resource use, will bridge the gap between research and real-world practice.

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Conflict of Interests

The authors declare no conflicts of interest associated with this research study. This work was conducted with full transparency and adherence to ethical research practices.

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