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Growth Stage–Dependent Variations in Nutrient Composition and *In vitro* Rumen Fermentation Characteristics of Underutilized Fabaceae Legumes

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ABSTRACT

Conventional legumes like soybean and cowpea are costly and often reserved for humans, highlighting the need for affordable, underutilized forage legumes for ruminant feeding. A comparative study, using a randomized complete block design (RCBD) with plots treated as blocks to account for soil variability, was conducted to evaluate the nutritive composition and in vitro fermentative characteristics of five underutilized Fabaceae forages; four cultivars of Mucuna pruriens (Tropical, Cream, Bush, and Black) and Canavalia ensiformis, harvested at four phenological stages (weeks 4, 8, 12, and 16). Proximate and fibre analyses were performed alongside in vitro gas production and degradation kinetics to assess their degradability potential for ruminant feeding. Statistical analyses were performed using the GLM procedure in Minitab Statistical Software at $p < 0.05$ using Tukey's test. Results showed significant differences ($p < 0.05$) in dry matter (DM), crude protein (CP), and fibre fractions (NDF, ADF) among the cultivars and growth stages. The CP peaked between weeks 8–12, followed by a decline at week 16, corresponding with an increase in NDF and ADF, suggesting a shift from soluble to structural carbohydrate dominance. Nitrogen-free extract (NFE) increased at mid-maturity, reflecting enhanced soluble carbohydrate availability. In vitro gas production mirrored chemical composition, rising from week 4 to a maximum at week 8–12 before declining at week 16. Tropical and Cream Mucuna cultivars consistently exhibited superior fermentability, while C. ensiformis displayed lower gas yields and degradability constants. The degradation kinetic parameters (b and c) confirmed that mid-maturity forages (week 8–12) provided optimal fermentative efficiency. Overall, early-to-mid harvests offered the best balance between nutrient density and fermentability, while late-matured forages were more fibrous and suited to maintenance diets. These findings highlight the potential of Mucuna pruriens cultivars and Canavalia ensiformis as sustainable, protein-rich forage options for tropical ruminant systems, but further in vivo studies are needed to confirm their efficacy in ruminant diets.

Keywords: *Underutilized forages, Mucuna pruriens, Canavalia ensiformis, in vitro gas production, forage maturity, ruminant nutrition.*

INTRODUCTION

Animal production systems face a significant challenge from the growing demand for animal protein, which is expected to increase by 14% worldwide by 2030 (Nykolyuk *et al*., 2021). This spike, caused by rising affluence and population, calls for creative solutions to fulfil the skyrocketing need in an environmentally responsible manner. Forages which include grasses, legumes and herbaceous plants become essential

elements in tackling this issue since they are vital in supplying livestock production systems with sustainable feed sources (Moorby, 2021; Tremblay *et al*., 2023).

Crucial aspects of animal performance, including growth, milk production and reproductive efficiency, are greatly impacted by the quality and nutritional value of forages (Kim *et al*., 2019; Kim *et al*., 2020). The problem still exists despite the copious amount of research conducted on the broader topic of forages, including digestibility, nutrient content and management techniques. As important factors that determine the nutritional value of forage for different animal species, current studies focus on chemical composition, which includes crude protein, fibre fractions, minerals and energy content (Chilibroste *et al*., 2015).

Further strides in forage research aim to develop improved varieties, enhancing yield, nutritional composition, disease resistance and environmental adaptability (NRC, 2007). These extensive studies not only contribute to the advancement of academic knowledge but also serve as a foundation for the development of efficient feeding plans, enhancements to animal performance and reduction of the environmental impact of livestock production (Prates *et al*., 2018). Ruminant animals have distinct digestive systems and mostly rely on forages especially grasses and legumes as sources of nourishment. For ruminants, the densely nutrient-rich and fibrous forages derived from grasses and legumes are ideal. According to Beauchemin *et al*. (2009) rumen microbes play a crucial role in the complex interactions between various forages by facilitating the fermentation of fibrous components, which provide vital nutrients required for growth and maintenance. Furthermore, the relevance of this relationship for the ruminant animals' nutrition, productivity and general health is highlighted by the fact that the protein content of forage legumes significantly helps in meeting their protein requirements (Chilibroste *et al*., 2015).

Poore and Nemecek (2018) reported that legumes are known for their sustainability and have a lower carbon footprint than foods derived from animals. Legumes that are not commonly used as feeder crops worldwide are known as underutilized legumes and using them is one of the most important ways to improve global food security. In addition to providing a sustainable source of protein during the switch to plant-based proteins during the protein transition, these legumes address the issue of food security in impoverished countries (Padulosi *et al*., 2013).

Soybeans (*Glycine max*), a well-known legume imported from temperate regions provide a portion of the protein needed for livestock production in most regions of the tropics and subtropics including Ghana. However, the high cost and genetic modification of soybeans have sparked interest in underutilized protein sources. Underutilized legumes, that have not been widely employed as a feeding crop, are a key component of the global food security equation since they reduce the excessive reliance on imported feeds high in protein (Purwandari *et al*., 2023).

The Velvet bean (*Mucuna pruriens var utilis*) and the Jack or sword bean (*Canavalia ensiformis*) are two subgroups of the legume family (Fabaceae) that stand out as a potential alternative source of protein for ruminants but are underutilized. Native to Asia and Africa, *Mucuna pruriens* is a tropical legume cover crop that is highly prized for its traditional uses as a food source, medicinal plant and as a potential protein supplement. Studies by Mekuriaw (2018), Wyse et al. (2022), Yusriani et al. (2021), and Chikagwa-Malunga et al. (2009) have demonstrated that supplementation with Mucuna foliage hay, characterized by its high crude protein content, significantly improves the nutritional value of low-quality forages such as maize stover and tropical grass hays, thereby enhancing ruminant performance.

The Jack bean (*Canavalia ensiformis*) is another underutilized legume. In South America, West Africa, Asia, and the South Pacific, jack beans are grown in tropical and subtropical climates. According to Sridhar and Seena (2006) the legume has 23–35% protein, 46–65% carbohydrates and 5–11% fibre. *Canavalia ensiformis* grows quickly and yields enormous, broad leaves and flat seeds, which can be used as leaf biomass to feed ruminants (Purwandari *et al*., 2023). As pertains to legumes, the Velvet and Jack beans have special qualities including turning atmospheric nitrogen into organic forms and improving soil fertility when used as cover crops and/or

a great source of green manure. Legumes are well-known for their symbiotic interactions with nitrogen-fixing bacteria (Büchi *et al*., 2015; Matata *et al.,* 2017). Compared to grasses, legumes have a higher nutritional value and include vital vitamins, minerals, and amino acids that are needed for animal growth (Purwandari *et al*., 2023). They are also a good source of energy for ruminants due to their better digestibility and lower fibre content (Osman *et al.,* 2019; Ojo *et al.,* 2021; Bhandari *et al*, 2023; Castro-Montoya and Albarrán-Portillo, 2023). Legume bean harvest practices are mainly influenced by soil conditions and geographic location (Eilitta *et al*., 2002). Beans are generally harvested 110 –270 days after planting (DAP) and plant leaf biomasses are collected 90 –120 DAP when cultivated for forage (Eilitta *et al*., 2002).

This study was conceptualized based on the recognition that, despite some prior scientific exploration of *Mucuna pruriens var utilis* and *Canavalia ensiformis*s cover crops and green manure crops, their utilization as forage crops is relatively limited compared to other legumes within the same Fabaceae family, such as cowpea (*Vigna unguiculata*) and soybean (*Glycine max*), especially in the Ghanaian context. Additionally, there is lack of clarity on the optimal time for harvest of these underutilized forage legumes to maximize their nutritive value. The degree to which maturity-related dynamics in nutritional composition differ among cultivars is also poorly understood, creating a knowledge gap. Therefore, the main aim was to evaluate the nutritional composition, fibre characteristics, and ruminal digestibility of five underutilized Fabaceae legumes; four cultivars of *Mucuna pruriens* (Tropical, Cream, Bush, and Black) and *Canavalia ensiformis,* harvested at four phenological stages (weeks 4, 8, 12, and 16) to determine their potential as sustainable feed resources for ruminants. It was hypothesized that both cultivar type and harvest age significantly influence the nutritional value, fibre composition, and ruminal fermentability of the selected Fabaceae legumes.

MATERIALS AND METHODS

Study Area

The agronomic study was conducted in the Asutifi North District of the Ahafo Region at Ahafo Kenyasi. The area lies between Latitudes 6°40' and 7°15' North and Longitudes 2°15' and 2°45' West (Agariga et al., 2021). The region is located in the wet semi-equatorial zone, which is characterized by two double rainfall maxima in June and October, with a mean annual rainfall between 1250mm and 2000mm. March through to June marks the beginning of the first rainy season and August through to October marks the beginning of the second (Agariga et al., 2021). During the two rainy seasons, relative humidity ranges from 75% to 80%, while the rest of the year it ranges from 70% to 80%. The soil type is the sandy loam, fully rich in nutrients such as Nitrogen and Phosphorus. It has free drainage thus suggested for food crops including corn, beans and cassava as well as tree crops like cocoa, citrus and coffee (Agariga et al., 2021). The chemical and nutritional analyses were conducted in the Nutritional Laboratory of the Department of Animal Science, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana.

Collection and Preparation of Leaf Samples

The leguminous seeds were obtained from the Centre for No -Till Agriculture at Amanchia in the Ashanti region. The experimental design utilised for the study was a randomized complete block design (RCBD). Plots were treated as blocks in this study because of the potential soil nutrient variability between plots. The five cultivars of cowpea were planted in five different blocks located in various areas of the field during the wet season. Each block contained five replicated plots of the five leguminous cultivars, which were; Tropical *Mucuna pruriens* (Tr-MP), Cream *Mucuna pruriens* (Cr-MP), Bush *Mucuna pruriens* (Bu-MP), Black *Mucuna pruriens* (Bl-MP) and *Canavalia ensiformis* (CE).

The agronomic study followed standard practices, examining the growth of the five forages. Each plot had a planting distance of 1m x 1m. Three seeds were sown per hole and thinned to one plant per hole after emergence. Weed control, thinning and staking were the cultural practices that were carried out and there was no fertilizer application. This deliberate choice aimed to assess the intrinsic nutrient composition of the leguminous forages without external inputs that could potentially affect the outcomes. The leaf and twig samples were harvested from each rep-

licated plant from the five cultivars on all the plots at 4, 8, 12 and 16 weeks respectively. The samples were air-dried for three days, then milled to pass through a 1mm sieve size and then sub sampled and stored in zip lock bags separately for proximate and detergent fiber analyses and *In vitro* gas production.

Chemical Analysis

The proximate compositions of the milled samples were determined using the procedures of AOAC (Horwitz, 1964). Briefly, dry matter was determined by oven-drying, ash by incineration, crude protein by the Kjeldahl method (N × 6.25), ether extract by solvent extraction, and crude fibre by acid–alkali digestion. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined following Van Soest et al. (1991) using detergent fractionation of cell wall components.

Dry Matter

The DM was estimated using the formula:

$$\%DM = \frac{\text{Weight of Dry Sample}}{\text{Weight of Fresh Sample}} \times 100 \quad \ldots.(1)$$

Crude protein

Crude protein was determined using the Kjeldahl method following the procedures of AOAC (Horwitz, 1964). Samples were digested with concentrated H_2SO_4 in the presence of a catalyst, followed by neutralization, distillation, and titration to determine nitrogen content. Crude protein was calculated as nitrogen × 6.25 (Equation 2):

$$\%CP = \text{Nitrogen x } 6.25 \quad \ldots.(2)$$

Ash

Ash content was determined according to AOAC (Horwitz, 1964) by incinerating samples in a muffle furnace at 600°C to constant weight. The residue was expressed as a percentage of the original sample weight (Equation 3):

$$\%\ Ash = \frac{\text{Weight of Ashed Sample}}{\text{Weight of Fresh Sample}} \times 100 \quad \ldots.(3)$$

Ether extract

Ether extract was determined using the Soxhlet extraction method as described by AOAC (Horwitz, 1964). Samples were continuously extracted with petroleum ether and the lipid fraction quantified gravimetrically after solvent removal. Percentage ether extract was calculated using Equation 4:

$$\%\ EE = \frac{\text{Weight of Extracted Fat}}{\text{Weight of Fresh Sample}} \times 100 \quad \ldots.(4)$$

Crude Fibre (CF)

Crude fibre was determined following the procedures of AOAC (Horwitz, 1964) through sequential acid and alkali digestion to remove soluble components, followed by drying and ashing of the residue. Crude fibre was expressed as the difference between initial sample weight and ash weight relative to the original sample (Equation 5):

$$\%\ \text{CF} = \frac{\text{Initial sample weight - Ash weight}}{\text{Initial sample weight}} \times 100 \ldots.(5)$$

Nitrogen free Extract (NFE)

Nitrogen-free extract was calculated according to AOAC (Horwitz, 1964) using the difference method:

$$\%NFE = 100 - (\%DM + \%CP + \%EE + CF + Ash) \quad \ldots.(6)$$

Detergent fibre analyses

Neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) were determined using the ANKOM 2000 system following Van Soest et al. (1991). NDF and ADF were obtained through detergent reflux and filtration to isolate cell wall fractions, while ADL was determined by treating ADF residue with 72% H_2SO_4. Residues were dried at 105°C to constant weight for gravimetric determination.

In vitro Gas Production (IVGP)

Rumen fluid used for the in vitro studies was obtained from 10 male N'dama beef cattle with an average age of 3 ½ years old and a live weight of 297 kg. The sheep were slaughtered at

the Kumasi Abattoir Company Limited, Ghana, and the rumen digesta was collected as soon as the carcasses were opened and placed in a pre-warmed vacuum flask. The digesta was strained through a four-layer cheese cloth under continuous CO_2 flushing to maintain anaerobic conditions. The rumen liquor was then mixed with buffer in a ratio of 1:4 (liquor: buffer) following the procedure of Menke et al., (1979). Two hundred milligrams of each milled forage sample were incubated with the rumen liquor–buffer mixture in calibrated glass syringes using standard procedures (Menke and Steingass, 1988). Incubation was conducted in a water bath at 39° C (Blu and Ørskov, 1993) in two independent runs. For each run, samples were incubated in triplicate and gas production was recorded at 3, 6, 12, 24, 48, 72, and 96 h, giving six statistical repetitions. Each run included two blanks containing only rumen liquor and buffer, and all gas values were corrected for blank incubation.

Statistical Analysis

Statistical analyses were performed using the GLM procedure in Minitab Statistical Software (version 19.0, Minitab, LLC, NY, US, 2019). Data were presented as means of three replicate samples. The plant species served as the experimental units, while chemical composition parameters (DM, CP, CF, EE, NFE, ash, NDF, and ADF) and *in vitro* gas production and degradation parameters (a and b) were the response variables. Significance was determined at $p < 0.05$ using Tukey's test. For *in vitro* gas production, an exponential curve was fitted using SigmaPlot (version 15.0, SYSTAT Software Inc.), applying the Ørskov and McDonald (1979) model as follows:

$$Y = b(1 - e - ct) \quad \ldots.(7)$$

Where:

Y = volume of gas produced at time t (ml)
b = *potential gas production (mL/200 mgDM)*
c = *rate at which gas was produced from the insoluble fraction (mL/hr),*
t = *incubation time.*

RESULTS AND DISCUSSION

Analytical dry matter (DM) composition

Table 1 shows the dry matter compositions at different harvesting times of the leguminous cultivars. Results show that DM differed significantly among cultivars at week 4, week 8 and week 12 ($p < 0.05$) but not at week 16 ($p > 0.05$). The trend was that *Black Mucuna* (Bl-MP), *Bush Mucuna* (Bu-MP) and *Tropical Mucuna* (Tr-MP) showed the highest DM at week 4 (≈82.7, 81.8, 81.7% respectively), while *Canavalia ensiformis* (CE) had the lowest (78.7%). By week 8 Tr-MP and Cream *Mucuna pruriens* (Cr-MP) reached a peak DM (98.39%), indicating a sharp rise in dry matter concentration at this stage. The CE peaked later (week 12, 87.03%), and by week 16 cultivar differences were no longer significant ($p > 0.05$), reflecting stabilization of moisture loss. Differences in DM across cultivars and harvest stages indicate that genetic makeup and growth stage strongly affect biomass buildup and water content**.** The early high DM of certain Mucuna cultivars suggests more rapid tissue maturation or lower initial moisture content compared with CE. The week-8 DM surge (particularly for Tr-MP and Cr-MP) suggests an optimal harvest window to maximise preservable biomass, a practical point for fodder conservation. These observations are consistent with general forage phenology where legumes can show cultivar-specific peaks in DM (Cabiddu et al., 2009). The later peak in CE agrees with reports that Canavalia species can accumulate DM more slowly than some Mucuna genotypes (Smith *et al.,* 2018). Practically, for silage or hay production, harvesting most of these Mucuna cultivars around week 8 will maximise DM for storage while *Canavalia ensiformis* may be harvested slightly later if higher DM is required.

Analytical crude protein (CP) composition

Table 2 provides summary of crude protein concentrations at different harvesting times of the leguminous cultivars. The data shows significant differences among treatments at weeks 4, 8 and 16 ($p < 0.05$) with no significant difference at week 12 ($p > 0.05$). At week 4, *Cream* and *Tropical Mucuna* were highest (~18.3–18.5%), while *Canavalia ensiformis* (CE) was lowest (14.85%). *Bush Mucuna* attained the highest CP

Table 1: Dry matter compositions of the leguminous cultivars at different harvesting times

Cultivar	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	81.70[a]	98.39[a]	84.37[b]	84.43
Cream Mucuna	79.79[bc]	98.39[a]	83.63[b]	81.73
Bush Mucuna	81.77[ab]	81.70[b]	85.07[b]	82.41
Black Mucuna	82.70[a]	80.57[bc]	84.87[b]	82.41
Canavalia ensiformis	78.73[c]	78.83[c]	87.03[a]	82.99
SEM	0.415	2.380	0.343	0.513
P-value	<0.001	<0.001	0.003	0.618

[a],[b],[c], Mean values within a column with different superscripts are significantly different (p < 0.05).

at week 16 (19.25%). Black Mucuna showed an increase to week 12 then a decline by week 16, suggesting temporal protein accumulation followed by dilution or senescence. The CP values for these Mucuna cultivars (~14–19%) reported in this study align with reported foliage ranges for *Mucuna pruriens* whole plant biomass (Okla et al., 2021; Yusriani *et al.,* 2021) and support previous findings that Mucuna foliage is a useful protein supplement (Wyse *et al.,* 2022). The CE CP values were comparable to Smith *et al.,* (2018) for whole-plant Canavalia (~15%) but are lower than seed protein ranges reported by Tilahun *et al.,* (2019), which is expected because seed protein is concentrated relative to vegetative biomass. The mid-season increases in CP followed by declines in some cultivars confirm observations that protein concentration can be diluted as structural carbohydrates (cell wall components) accumulate with maturity (Olfaz *et al.,* 2018). Optimising protein supply for ruminants requires harvesting at stages when crude protein (CP) concentration is maximal but not yet diluted by advancing structural growth. In this study, the plateau or pre-dilution phase for most Mucuna cultivars occurred between weeks 8 and 12, corresponding to the period of highest protein yield relative to biomass. Notably, Bush Mucuna maintained elevated CP levels even at week 16, indicating potential suitability for situations demanding higher protein content, such as lactating or growing animals. All evaluated forages exhibited markedly superior nutritional profiles compared with typical dry-season crop residues like rice straw, which contains approximately 5% CP (Babayemi *et al.,* 2020). The *Mucuna pruriens* cultivars also compared favourably with *Avena sativa* (15% CP), commonly used as a dry-season forage, and were comparable to *Canavalia ensiformis* but somewhat lower than *Lolium multiflorum* foliage, which averages around 20% CP (Andriarimalala *et al.,* 2021). More so, the crude protein contents of the *Mucuna pruriens* cultivars and *Canavalia ensiformis* observed in this study fall within the 17.0 –18.5% range, closely comparable to the 17.0–18.52% reported for selected *Vigna unguiculata* (cowpea) genotypes by Wyse *et al.,* (2022). This similarity suggests that these underutilized legumes have protein concentrations sufficient to meet the maintenance and moderate production requirements of ruminants, positioning them as viable protein sources alongside cowpea.

Analytical crude fat composition

Table 3 shows the crude fat concentrations at different harvesting times of the leguminous cultivars. The crude fat differed among cultivars at weeks 4, 8 and 16 ($p < 0.05$), but not at week 12 ($p > 0.05$). Black Mucuna recorded the highest EE at multiple sampling points (9.67% at wk4 and 9.42% at wk16). *Canavalia ensiformis* (CE) had lower values at wk4 and wk8 but increased to 9.62% at wk12. The crude fat results suggest clear cultivar differences in lipid reserves or cuticular wax accumulation, with Black Mucuna exhibiting relatively higher lipid

content compared with *C. ensiformis* and the other Mucuna cultivars. While elevated crude fat can enhance the energy density of forages, the overall levels observed remain within moderate ranges. Compared with published data, Yeanpet *et al.,* (2022) reported approximately 2.4% crude fat in Mucuna foliage, lower than the present findings, which may reflect variations in plant parts sampled, environmental conditions, or analytical extraction methods. Such discrepancies are common in forage studies and emphasize the importance of standardized sampling procedures (Smith *et al.,* 2018). Cultivars with slightly higher crude fat, such as Black Mucuna, may provide marginal benefits in energy supply; however, differences in crude fat are likely secondary to crude protein and fibre fractions in determining overall feeding value.

Analytical ash composition

The ash content of the leguminous cultivars across the four harvesting periods is presented in Table 5. Significant differences among cultivars were observed at weeks 8, 12, and 16 ($p < 0.05$), whereas week 4 showed no significant variation ($p > 0.05$). Across sampling times, *Black Mucu-*

Table 2: Crude protein compositions of the leguminous cultivars at different harvesting times

Cultivar	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	18.34^{ab}	17.35^{b}	8.40	17.93^{a}
Cream Mucuna	18.46^{a}	16.50^{c}	8.52	17.60^{bc}
Bush Mucuna	17.72^{b}	18.29^{a}	9.28	19.25^{a}
Black Mucuna	16.61^{c}	16.78^{bc}	8.92	14.64^{d}
Canavalia ensiformis	14.85^{d}	16.02^{c}	9.62	16.20^{c}
SEM	0.364	0.217	0.194	0.437
P-value	<0.001	<0.001	0.238	<0.001

$^{a,b,\ c,d,}$ *Mean values within a column with different superscripts are significantly different ($p < 0.05$).*

Table 3: Crude fat compositions of the leguminous cultivars at different harvesting times

Cultivar	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	8.60^{ab}	8.10^{ab}	8.40	7.87^{ab}
Cream Mucuna	9.16^{ab}	7.55^{ab}	8.52	7.23^{a}
Bush Mucuna	9.32^{ab}	7.62^{ab}	9.28	7.78^{ab}
Black Mucuna	9.67^{a}	8.67^{a}	8.92	9.42^{a}
Canavalia ensiformis	7.73^{b}	6.62^{b}	9.62	7.20^{b}
SEM	0.228	0.220	0.194	0.265
P-value	0.029	0.015	0.238	0.019

^{a,b,} *Mean values within a column with different superscripts are significantly different ($p < 0.05$).*

Table 4: Crude fibre compositions of the leguminous cultivars at different harvesting times

Cultivars	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	13.50	14.13	13.07[b]	18.60
Cream Mucuna	13.88	13.87	16.53[ab]	20.77
Bush Mucuna	14.50	16.10	17.13[ab]	18.00
Black Mucuna	13.92	14.03	17.13[ab]	16.30
Canavalia ensiformis	13.55	11.73	20.37[a]	18.67
SEM	0.646	1.100	0.735	0.564
P-value	0.993	0.858	<0.009	0.150

[a,b]*Mean values within a column with different superscripts are significantly different ($p < 0.05$)*

na and *Canavalia ensiformis* (CE) consistently exhibited relatively higher ash concentrations (*Black Mucuna*: 13.20% at week 4 and 12.23% at week 8; *C. ensiformis*: 13.35% at week 4). In contrast, *Tropical* and *Cream Mucuna* generally recorded lower ash values at later harvests, suggesting possible cultivar-specific mineral accumulation patterns. The observed differences in ash content likely reflect inherent genetic variation in mineral uptake efficiency and translocation, as well as environmental or soil nutrient effects. Elevated ash levels indicate higher total mineral matter and could be associated with greater uptake of macro- and microelements such as calcium, potassium, and magnesium. The comparatively higher ash content in *Black Mucuna* suggests potential agronomic value for soil nutrient recycling or green manuring, consistent with earlier observations that leguminous cover crops can enhance soil fertility through mineral deposition (Smith *et al.,* 2018). However, excessive ash may slightly reduce the organic energy density of the forage, potentially influencing its feed value. Thus, interpretation should consider both nutritional and agronomic objectives. For feed purposes, moderate ash levels are desirable to maintain energy balance, whereas for soil enrichment applications, cultivars with higher ash content such as Black Mucuna*, C. ensiformis* may be preferable due to their mineral restitution potential.

Analytical Nitrogen-Free Extract (NFE) Composition

The nitrogen-free extract (NFE) contents of the five leguminous cultivars at different harvesting

Table 5: Ash compositions of the leguminous cultivars at different harvesting times

Cultivars	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	10.20	8.70[b]	7.73[c]	6.97[c]
Cream Mucuna	9.22	7.60[c]	12.17[a]	8.10[bc]
Bush Mucuna	9.78	7.70[c]	9.84[b]	7.67[bc]
Black Mucuna	13.20	12.23[a]	8.57[c]	12.87[a]
Canavalia ensiformis	13.35	9.17[b]	8.13[c]	8.60[b]
SEM	0.695	0.457	0.437	0.570
P-value	0.152	<0.001	<0.001	<0.001

[a,b,c]*Mean values within a column with different superscripts are significantly different ($p < 0.05$)*

stages are summarized in Table 6. The data showed significant differences observed only at week 12 ($p < 0.05$), whereas variations at weeks 4, 8, and 16 were not significant ($p > 0$ 0.5). Across the growth stages, NFE, representing the soluble carbohydrate fraction, tended to peak around week 12 in several cultivars. *Tropical Mucuna* showed the highest value at this stage (52.53%), while *Cream Mucuna* and *C. ensiformis* exhibited comparatively lower levels. This mid-season increase suggests enhanced accumulation of non-structural carbohydrates such as starches and soluble sugars as plants transition from vegetative expansion toward reproductive development. The observed trend aligns with established plant physiological patterns, where soluble carbohydrate reserves increase temporarily before being mobilized for flowering or pod formation (Wyse *et al.,* 2022). Such transient carbohydrate enrichment can improve the fermentable energy supply for ruminants, thereby enhancing microbial activity and rumen efficiency. The inter-cultivar differences observed here indicate genetic variability in carbohydrate partitioning and may serve as a useful basis for selecting energy-dense forage materials within the *Mucuna* and *Canavalia* genera. From a practical standpoint, harvesting at mid-growth (around week 12) appears optimal for maximizing NFE and overall energy value of the foliage. Cultivars like *Tropical Mucuna*, which exhibited superior NFE at this stage, could therefore provide better energy supplementation potential in ruminant feeding systems compared with later, more fibrous harvests.

Analytical Neutral Detergent Fibre (NDF) Composition

Table 7 presents the neutral detergent fibre (NDF) contents of the five leguminous cultivars across the four harvesting stages. The NDF differences among cultivars were significant at week 12 ($p < 0.05$) and week 16 ($p < 0.05$), but non-significant at weeks 4 and 8. A clear pattern of increasing NDF concentration with advancing plant age was observed, indicating a progressive build-up of structural carbohydrates. The highest NDF values occurred at week 16, notably in *Bush Mucuna* (57.47%), while *Black Mucuna* and *Tropical Mucuna* also showed elevated levels at later stages. This trend reflects normal physiological maturation, where deposition of cellulose, hemicellulose, and lignin in the cell wall intensifies, reducing cell solubility and digestibility. These results are consistent with earlier findings for forage legumes, where NDF levels rise with advancing maturity (Wyse *et al.,* 2022). The mean NDF values observed at 16 weeks (~53.6%) are comparable to those reported by Wyse *et al.,* (2022), while lower than the 66.2% reported by Yeanpet *et al.,* (2022), suggesting the influence of genotype and environ-

Table 6: Nitrogen free extract compositions of the leguminous cultivars at different harvesting times

Cultivars	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	49.35	51.72	52.53[a]	48.63
Cream Mucuna	49.27	56.46	45.48[b]	46.30
Bush Mucuna	48.68	50.30	46.80[b]	47.30
Black Mucuna	46.60	48.25	46.75[b]	46.78
Canavalia ensiformis	50.51	56.46	45.37[b]	49.33
SEM	1.27	1.270	0.799	0.601
P-value	0.853	0.265	0.002	0.518

[a,b]*Mean values within a column with different superscripts are significantly different ($p < 0.05$)*

Table 7: Neutral detergent fibre compositions of the leguminous cultivars at different harvesting times

Cultivars	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	39.13	41.97	48.47[a]	54.77[ab]
Cream Mucuna	29.30	43.20	46.47[ab]	53.53[ab]
Bush Mucuna	36.70	42.60	41.30[b]	57.47[a]
Black Mucuna	39.13	47.83	49.60[a]	48.43[b]
Canavalia ensiformis	33.23	42.57	43.97[ab]	51.40[ab]
SEM	1.730	1.290	0.939	1.040
p-value	0.337	0.663	0.006	0.032

[a,b]*Mean values within a column with different superscripts are significantly different ($p < 0.05$)*

mental conditions on fibre deposition. Compared with grasses, these moderate NDF levels indicate relatively better forage quality and potential for higher voluntary intake, as legumes typically possess less structural fibre and higher digestible fractions. From a practical feeding perspective, the steady increase in NDF with age implies that delayed harvesting could reduce palatability and intake potential due to lower rumen degradability. For optimal forage quality, harvesting before week 12, when NDF remains moderate would enhance voluntary intake and animal performance. Beyond this stage, rising NDF and concurrent lignification may constrain digestibility and limit energy availability to ruminants. Importantly, the levels of NDF observed in the present study were lower than those typically reported for cereal or grass hays and silages, which can reach up to 60% NDF. Structural carbohydrates such as NDF are critical determinants of forage quality and digestibility in ruminant nutrition (Arif *et al.,* 2022). Consequently, the comparatively lower fibre levels in these leguminous forages suggest a higher potential for voluntary intake and improved digestibility relative to conventional cereal or grass hays.

Analytical Acid Detergent Fibre (ADF) Composition

Table 8 presents the acid detergent fibre (ADF) contents of the leguminous cultivars across the four harvesting stages. The data revealed significant differences among cultivars at weeks 8, 12, and 16 ($p < 0.05$), while week 4 differences were marginal ($p > 0.05$). A general increase in ADF concentration with plant maturity was observed, reflecting the progressive deposition of cellulose and lignin within the cell wall matrix. *Cream Mucuna* and *Canavalia ensiformis* (CE) exhibited particularly high ADF levels at weeks 12–16 (approximately 38%), which corresponded to reduced digestibility potential compared to the other *Mucuna* cultivars. Such fibre accumulation is characteristic of advancing vegetative and structural development, leading to reduced cell solubility and higher proportions of indigestible fractions. The progressive increase in ADF observed with advancing plant maturity in this study is consistent with established patterns reported by Diop (2021) and Wyse *et al.,* (2022), who noted a linear rise in ADF as structural carbohydrates accumulate and cell wall lignification intensifies. The mean ADF value at 16 weeks (~33.64%) was notably lower than the ~44.8% reported by Yeanpet *et al.,* (2022), suggesting superior fibre digestibility in the current forages, likely influenced by genotype, soil fertility, and environmental conditions. Across all cultivars and harvest periods, ADF levels remained within the 20–45% range previously reported for tropical forages (Asaolu *et al.,* 2011; Martens *et al.,* 2012), indicating good potential for rumen degradability and nutrient availability. According to Nguku *et al.,* (2016), ADF serves as a key

Table 8: Acid detergent fibre compositions of the leguminous cultivars at different harvesting times

Cultivars	Week 4	Week 8	Week 12	Week 16
Tropical Mucuna	29.27	25.03[b]	32.33[b]	33.67[b]
Cream Mucuna	24.87	26.27[b]	38.10[a]	38.13[a]
Bush Mucuna	22.33	26.00[b]	32.13[b]	32.57[b]
Black Mucuna	23.37	33.50[a]	29.23[c]	30.20[b]
Canavalia ensiformis	20.93	24.83[b]	33.23[b]	38.49[a]
SEM	1.030	0.933	0.801	0.090
p-value	0.071	<0.001	<0.001	<0.001

[a,b]Mean values within a column with different superscripts are significantly different ($p < 0.05$)

indicator of forage digestibility; thus, the moderate ADF values observed here imply acceptable digestibility for most ruminant classes. However, when ADF content approaches or exceeds 35–40%, as seen in *Cream Mucuna* and *C. ensiformis* at later harvests, digestibility and voluntary intake may decline, reducing feeding value for high-producing animals (Wyse *et al.,* 2022). Therefore, to optimize fibre utilization and energy yield, harvesting between 8 and 12 weeks before ADF surpasses 30–35%, is recommended, particularly for lactating or growing ruminants with higher nutrient demands.

In vitro Gas Production and Fermentation Kinetics of the Harvested Cultivars

Further analysis of the forage cultivars harvested at different growth stages was conducted using the *in vitro* gas production technique, a laboratory fermentation assay that simulates rumen conditions to evaluate the rate and extent of substrate degradation, providing insight into the fermentative characteristics and feeding value of the forages for ruminant nutrition. The *technique* allows for a controlled environment, mimicking the rumen conditions, enabling researchers to measure gas production over time (Menke *et al*., 1979; Menke and Steingass, 1988; Bovera *et al*., 2011; Storm *et al*., 2018; Sarkwa *et al*., 2020). Generally, it reflects the extent of the fermentation and digestibility of feed. Figure 1 illustrates the cumulative *in vitro* gas production (mL/200 mg DM) of the forages (cultivars of *Mucuna pruriens* and *Canavalia ensiformis*) harvested at week 4 across incubation times. Gas production increased sharply within the first 48 hours and plateaued between 72 and 96 hours of incubation, signifying rapid fermentation of readily degradable substrates. Among the cultivars, Tropical *Mucuna pruriens* exhibited the highest cumulative gas volume, followed by C. ensiformis, Black *Mucuna pruriens*, Cream *Mucuna pruriens*, while Bush *Mucuna pruriens* recorded the lowest yield. This pattern is consistent with the dominance of soluble carbohydrates and crude protein, and the relatively low levels of structural fibre (ADF and NDF) in young vegetative forage tissue (Osafo *et al.,* 2023). At this early stage of maturity, the high gas yield and steep fermentation curve reflect rapid microbial colonization, as the substrates are predominantly soluble and easily fermentable. Such a pattern typifies early growth-phase forages, where the cellular contents exceed cell wall constituents (NDF, ADF), supporting efficient microbial activity and high ruminal degradability (Menke *et al.,* 1979; Menke & Steingass, 1988). However, despite the rapid fermentation rate, the total gas volume remained moderate, likely due to the limited accumulation of fermentable biomass at this immature stage. Consequently, week 4 forages, while highly digestible, may offer lower total energy per unit area due to reduced dry matter yield. Table 9 presents the degradation

Table 9: Degradation kinetics of the incubated cultivar samples at week 4

Variable	Tropical Mucuna	*Cream Mucuna*	*Bush Mucuna*	*Black Mucuna*	*Canavalia ensiformis*	SEM	P-value
b (%)	18.52[a]	19.06[a]	17.84[ab]	18.10[ab]	16.92[b]	0.482	0.019
c (h^{-1})	0.041[ab]	0.045[a]	0.049[a]	0.043[ab]	0.038[b]	0.004	0.027

[a,b]Means with different superscripts in a row differ significantly (P<0.05); b (%) = potentially fermentable but insoluble fraction; c = rate of fermentation of b. SEM = standard error of means; P-value = probability value

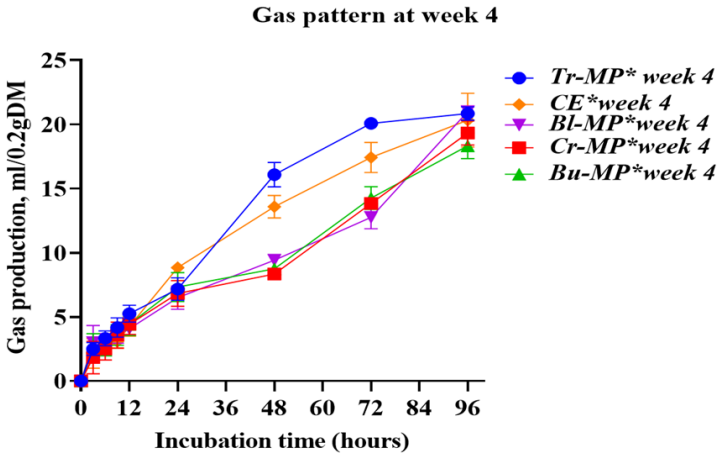


Figure 1: Cumulative *in vitro* gas production (mL/200gdm) of the forages (cultivars of *M. pruriens* and *C. ensiformis*) harvested at week 4

kinetics of the incubated samples at week 4. The potentially fermentable but insoluble fraction (b) ranged from 16.92% in *C. ensiformis* to 19.06% in Cream Mucuna, with Tropical and Cream Mucuna showing significantly higher ($p < 0.05$) values than Canavalia. The fermentation rate constant (c) was highest in Bush (0.049 h^{-1}) and Cream Mucuna (0.045 h^{-1}), indicating that these cultivars supported faster fermentation of the degradable fraction, whereas *C. ensiformis* recorded the slowest rate (0.038 h^{-1}). Integrating these results with the cumulative gas production pattern, it can be inferred that Bush Mucuna, despite lower total gas output, fermented more rapidly, suggesting that its degradable fraction was composed mainly of soluble, rapidly fermentable components. In contrast, Tropical Mucuna, with a higher b-fraction and moderate fermentation rate, sustained fermentation over a longer incubation period, explaining its superior total gas volume. These findings align with previous reports indicating that forage maturity influences fermentability and gas output through variations in cell wall composition and lignification (Osafo *et al.,* 2023; Sasu *et al.,* 2023). The observed high fermentability and efficient fermentation kinetics at week 4 imply that early-harvest forages are ideal as energy supplements in high-performance ruminant diets, where rapid ruminal fermentation and microbial protein synthesis are desirable. However, as suggested by Storm *et al.,* (2012) and Bovera *et al.,* (2011), the limited dry matter yield and lower structural fibre at this stage may reduce rumen fill and chewing activity if such forages are used as the sole roughage source. Overall, week 4 forages represent an early, highly fermentable growth phase, rich in soluble carbohydrates and proteins

but limited in total yield. These results establish a baseline for Figure 2 (week 8), where advancing plant maturity is expected to shift the balance towards higher fibre accumulation and structural carbohydrate content, potentially moderating fermentation rate and gas production while increasing total degradable matter and biomass yield.

Figure 2 presents the cumulative *in vitro* gas production (mL/200 mg DM) of the *Mucuna pruriens* and *Canavalia ensiformis* cultivars harvested at week 8 across 96 hours of incubation. Gas production increased markedly compared to week 4, with the most pronounced rise occurring between 24 and 60 hours, an indication of heightened microbial activity and a stronger fermentation response to substrates of intermediate maturity. Among the cultivars, Cream *Mucuna pruriens* produced the highest cumulative gas volume, followed by Black Mucuna, Tropical Mucuna, and Bush Mucuna, while *C. ensiformis* recorded the lowest gas yield. This enhanced gas output across the cultivars suggests that week 8 represents a physiological phase where the forage matrix contains a balanced proportion of soluble and structural carbohydrates, favoring sustained fermentation. The steep slopes of the gas curves during the early incubation phase (0–60 h) reflect an increased presence of readily fermentable carbohydrates and moderate cell wall fractions (NDF, ADF). According to Menke and Steingass (1988) such substrates promote active microbial colonization and efficient energy release in the rumen. The high gas volumes observed, particularly in Cream *Mucuna pruriens*, indicate optimal substrate availability and nutrient synchronization, contributing to superior energy yield and feed efficiency. Supporting these observations, Table 10 presents the degradation kinetics of the same cultivars at week 8. The potentially fermentable but insoluble fraction (b) ranged from 21.92% in *C. ensiformis* to 25.33% in Tropical Mucuna, with Tropical and Cream Mucuna exhibiting significantly higher ($p < 0.05$) values than C. ensiformis. The fermentation rate constant (c) was highest in Bush Mucuna (0.044 h^{-1}), followed by Tropical Mucuna (0.039 h^{-1}), and lowest in *C. ensiformis* (0.035 h^{-1}). These results suggest that at week 8, the Mucuna cultivars combined both a high degradable fraction and moderate fermentation rate, indicators of efficient ruminal fermentability and energy conversion (Gasmi-Boubaker *et al.,* 2005; Basha *et al.,* 2012). Integrating the gas production and degradation kinetics results, the forages at week 8 exhibited a clear shift from the early, highly soluble substrate dominance (as in week 4) toward a more balanced nutritional composition. The elevated b-fraction values across cultivars indicate greater potential degradability of the insoluble fraction, while the moderate c-values reflect sustained fermentation rather than rapid depletion. Cream Mucuna in particular demonstrated superior gas production and substantial b-fraction values, implying that its fermentation profile supports both immediate and extended microbial activity, a favorable attribute for ruminant feed efficiency. These findings confirm that week 8 represents an optimal harvest point for achieving maximum ruminal energy yield without significant loss in digestibility. The balance between cell contents and cell wall carbohydrates at this stage promotes both microbial growth and sustained gas production, consistent with the reports of Osafo *et al.,* (2023) and Sasu *et al.,* (2023), who emphasized that moderate plant maturity enhances overall digestibility and volatile fatty acid production. In summary, it is clearly seen that as the legume's maturity advances further toward week 12 (Figure 3), a gradual shift in gas production pattern is expected, reflecting increasing structural carbohydrate content and declining fermentation efficiency.

Figure 3 illustrates the cumulative *in vitro* gas production (mL/200 mg DM) of the *Mucuna pruriens* cultivars and *Canavalia ensiformis* harvested at week 12. Gas volumes continued to increase across all cultivars, reflecting the progressive development of fermentable substrate with advancing maturity. Cream *Mucuna pruriens* again exhibited the highest cumulative gas production, followed closely by Black and Bush *Mucuna pruriens*, while Tropical *Mucuna pruriens* and *C. ensiformis* recorded comparatively lower gas yields. This consistent trend indicates that the Cream and Black cultivars maintain superior fermentative efficiency throughout growth, likely due to their balanced carbohydrate and moderate fibre profiles. Despite con-

Table 10: Degradation kinetics of the incubated cultivar samples at week 8.

Variable	Tropical Mucuna	*Cream Mucuna*	*Bush Mucuna*	*Black Mucuna*	*Canavalia ensiformis*	SEM	p-value
b (%)	25.33^{a}	23.45^{ab}	22.80^{ab}	23.18^{ab}	21.92^{b}	0.526	0.013
c (h^{-1})	0.039^{ab}	0.037^{ab}	0.044^{a}	0.036^{ab}	0.035^{b}	0.003	0.021

^{a,b}*Means with different superscripts in a row differ significantly (P<0.05); b (%) = potentially fermentable but insoluble fraction; c = rate of fermentation of b. SEM = standard error of means; P-value = probability value*

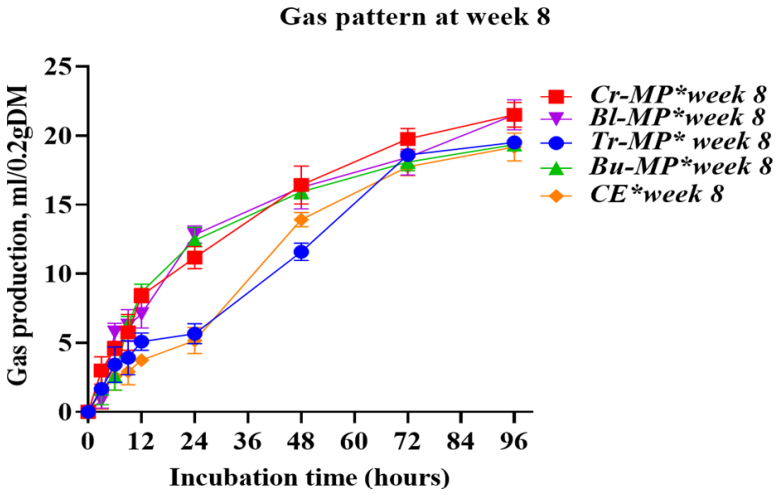


Figure 2: Cumulative *in vitro* gas production (mL/200gdm) of the forages (cultivars of *M. pruriens* and *C. ensiformis*) harvested at week 8

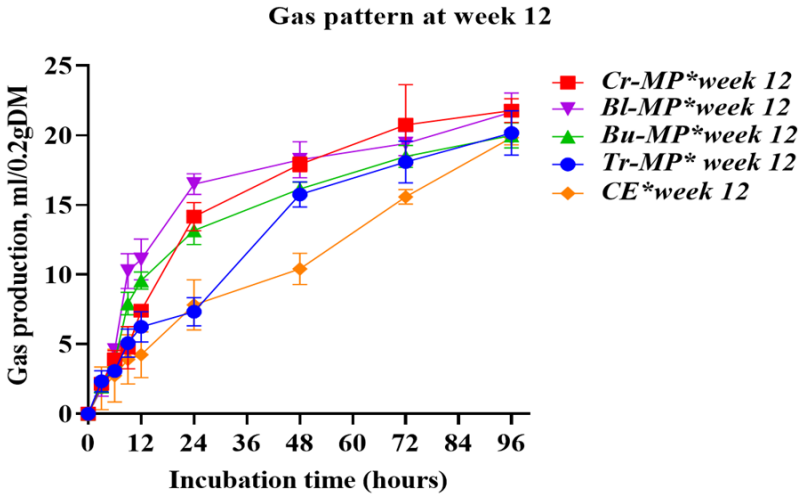
tinued gas production, a slight flattening of the gas curves beyond 72 hours was evident across all species, suggesting that microbial fermentation slowed as structural fibre components (NDF and ADF) increased, limiting microbial accessibility to the residual substrate. This pattern aligns with the biochemical transition typical of mid- to late-maturity tropical legumes, where cell wall lignification and lower soluble carbohydrate content begin to constrain ruminal degradation (Sreekala *et al.,* 2020). Nevertheless, the sustained gas volume reflects the persistence of moderately fermentable fractions and nitrogen -free extract (NFE), indicating that week 12 forages still support substantial microbial activity and energy release potential.

Table 11 complements the gas production patterns by detailing the degradation kinetics of the incubated samples. The potentially degradable but insoluble fraction (b) ranged from 20.65% in *C. ensiformis* to 23.40% in Tropical Mucuna, with Cream, Bush, and Black Mucuna showing intermediate yet comparable values. The fermentation rate constant (c) varied between 0.029 h^{-1} in *C. ensiformis* and 0.038 h^{-1} in Black Mucuna, indicating that while the amount of fermentable substrate remained relatively stable, the rate of microbial fermentation had slowed slightly compared with week 8. The reduction in "c" values signifies the onset of maturity-related fibre accumulation and partial cross-linking of lignocellulosic structures (Menke and Steingass, 1988). Collectively, the gas production and kinetic data suggest that week 12 represents a transitional phase in forage quality. Although fermentation remains efficient, the increasing fibre content begins to reduce degradation rates and perhaps microbial access to soluble carbohydrates. From a feeding perspective, this stage still provides adequate fermentability and digest-

Table 11: Degradation kinetics of the incubated cultivar samples at week 12

Variable	*Tropical Mucuna*	*Cream Mucuna*	*Bush Mucuna*	*Black Mucuna*	*Canavalia ensiformis*	SEM	P-value
b (%)	23.40[a]	22.06[ab]	21.73[ab]	22.21[ab]	20.65[b]	0.497	0.018
c (h^{-1})	0.031[ab]	0.034[a]	0.036[a]	0.038[a]	0.029[b]	0.003	0.025

[a,b]Means with different superscripts in a row differ significantly (P<0.05); b (%) = potentially fermentable but insoluble fraction; c = rate of fermentation of b. SEM = standard error of means; P-value = probability value



ible energy but signals the approaching decline typical of late-maturity tropical legumes. Thus, harvesting between weeks 8 and 12 would sustain high gas production while maintaining optimal degradability and nutritive value for ruminant feeding systems.

Figure 4 presents the cumulative in vitro gas production (mL/200 mg DM) of the *Mucuna pruriens* cultivars and *Canavalia ensiformis* harvested at week 16. The overall cumulative gas volumes declined markedly across all cultivars, indicating reduced fermentation efficiency at late maturity. *Canavalia ensiformis* and Cream *Mucuna pruriens* maintained moderate gas yields, followed by Tropical and Bush *Mucuna pruriens*, while Black *Mucuna pruriens* recorded the lowest cumulative gas production. This downturn in gas volume corresponds with the compositional shift typical of advancing physiological maturity, where neutral detergent fibre (NDF) and acid detergent fibre (ADF) fractions increase while soluble carbohydrate and crude protein concentrations decline (Yusriani *et al.,* 2021). The subdued gas production and slower cumulative curve patterns beyond 48 hours of incubation suggest a substantial reduction in microbial accessibility and substrate degradability due to increased lignification and cell wall cross-linking, which hinder microbial colonization and enzymatic hydrolysis. These findings support the assertion that late-harvested tropical legumes exhibit diminished fermentation rates and lower ruminal energy release (Ojo *et al.,* 2018; Osman *et al.,* 2023). Consequently, the forages harvested at week 16 are best suited for maintenance rations or low-production systems, where moderate digestibility suffices without the need for high fermentative energy supply. Table 12 reinforces the gas production trends through the degradation kinetics parameters. The potentially degradable but insoluble fraction (b) ranged from 19.76% in *C. ensiformis* to 24.43% in Tropical Mucuna, with significant cultivar variation (P < 0.05). Although the

Table 12: Degradation kinetics of the incubated cultivar samples at week 16

Variable	Tropical Mucuna	*Cream Mucuna*	*Bush Mucuna*	*Black Mucuna*	*Canavalia ensiformis*	SEM	P-value
b (%)	24.43[a]	21.05[ab]	20.82[b]	21.75[ab]	19.76[b]	0.511	0.016
c (h^{-1})	0.017[b]	0.036[ab]	0.044[a]	0.031[ab]	0.031[ab]	0.003	0.023

[a,b]*Means with different superscripts in a row differ significantly (P<0.05); b (%) = potentially fermentable but insoluble fraction; c = rate of fermentation of b. SEM = standard error of means; P-value = probability value*

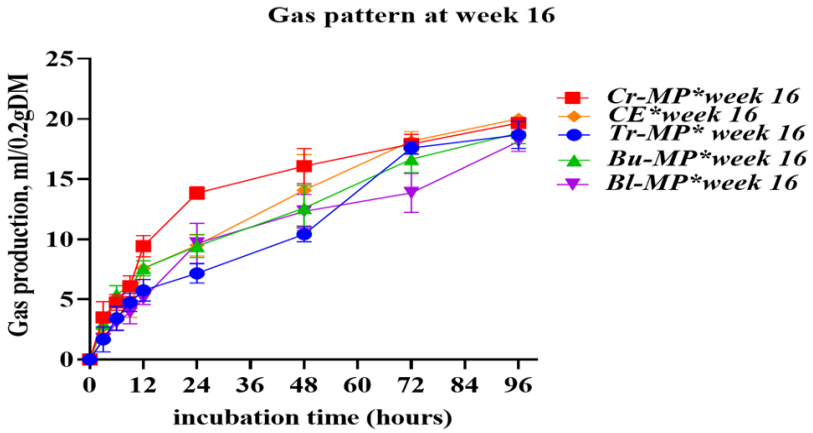


Figure 4: Cumulative *in vitro* gas production (mL/200gdm) of the forages (cultivars of *M. pruriens* and *C. ensiformis*) harvested at week 16.

"b" fraction for some Mucuna cultivars remained within the mid-range observed at week 12, the fermentation rate constant (c) showed a pronounced decline, dropping to 0.017 h^{-1} in Tropical Mucuna, the lowest across all growth stages. In contrast, Bush Mucuna retained the highest rate (0.044 h^{-1}), suggesting that cultivar-specific morphological or structural traits influence degradability under advanced maturity. The overall pattern of gas production and degradation kinetics across the sampling timeline (weeks 4–16) exhibits a parabolic relationship with maturity, characterized by a sharp rise from early growth (week 4), a peak at intermediate maturity (week 8–12), followed by a decline at week 16. This trajectory mirrors the biochemical transition from soluble to structural carbohydrate dominance, reflecting the trade-off between yield and nutritional quality (Menke and Steingass, 1988; Osafo *et al.,*2023). From a nutritional management perspective, the week 16 harvest represents a threshold of diminishing fermentative return, marking the onset of structural rigidity and lower degradable organic matter. Therefore, while late-stage forages contribute bulk of roughage, they are best utilized in maintenance feeding systems or combined with energy-dense supplements to balance ruminal fermentation efficiency.

CONCLUSION

This study revealed that cultivar type and growth stage significantly influenced the nutritional composition and fermentative characteristics of the underutilized Fabaceae forages. Crude protein (CP) and nitrogen-free extract (NFE) contents peaked between weeks 8 and 12, coinciding with optimal fermentability, while neutral detergent fibre (NDF) and acid detergent fibre (ADF) increased steadily with maturity, reflecting greater structural lignification. The *in vitro* gas pro-

duction patterns mirrored these compositional shifts, reaching a maximum at mid-harvest and declining thereafter, indicating reduced microbial accessibility of substrates with advancing age. Among the cultivars, Tropical and Cream *Mucuna pruriens* consistently demonstrated superior gas production and degradation kinetics, suggesting higher ruminal degradability and metabolizable energy potential compared to *Canavalia ensiformis*. From a feeding standpoint, harvesting at weeks 8–12 offers the best compromise between protein supply, energy yield, and fibre digestibility, ideal for high-producing ruminants, while later harvests may serve maintenance or soil-enrichment roles. Consequently, *Mucuna pruriens* cultivars, particularly the Tropical and Cream accessions, emerged as promising dry-season protein supplements in tropical livestock systems. Future research should validate these *in vitro* results through *in vivo* digestibility and animal performance trials, assess mineral and anti-nutritional profiles for safe inclusion levels, and evaluate agronomic resilience under varying ecological conditions to support sustainable forage utilization and integrated livestock–crop production systems.

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