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Enteric methane emission response to peanut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) haulms supplementation in zebu cattle diets

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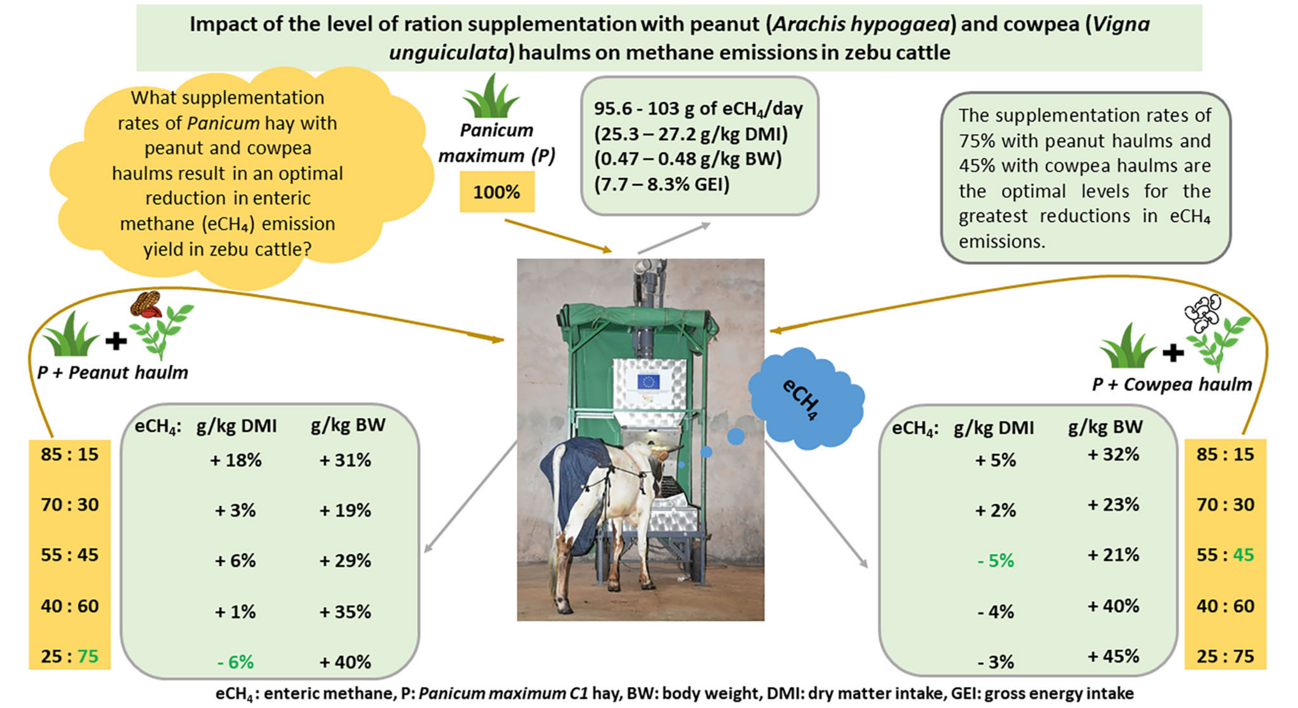
Improving the quality of ruminant rations is a promising strategy for mitigating the climate impact of livestock farming in West Africa. Legume crop coproducts such as peanut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) haulms are a high-protein fodder commonly used by agropastoral farmers during the dry season. This study evaluated their potential to reduce enteric methane (eCH_4) emissions when used as supplements for *Panicum maximum* C1 hay. Ten Sudanese Fulani zebu bulls (49 ± 1.2 months; 183.7 ± 15.9 kg) were housed individually and fed 11 diets *ad libitum*: a control diet of 100% *P. maximum* and 10 experimental diets combining *P. maximum* with either peanut or cowpea haulms at ratios of 85:15, 70:30, 55:45, 40:60, and 25:75. Each trial lasted 21 days, comprising a 14-day adaptation period and a 7-day data collection period for feed intake, digestibility, and eCH_4 emissions. The latter were measured six times daily using the GreenFeed system. Supplementation increased protein content by 47.5% to 183.5% and ADL by 2.6% to 48.2% while reducing the content of crude fiber, NDF, and ADF. Feed intake increased by 17.8% to 49.1% ($p < 0.05$), and digestibility improved by 4.6% to 9.9% ($p < 0.05$). Peanut haulms reduced eCH_4 yield by up to 6.1% ($p < 0.05$), while cowpea haulms achieved reductions of 3.7%–4.8% ($p = 0.14$). The most effective mitigation was achieved with 75% peanut or 45% cowpea haulms, confirming the potential of legume coproducts to enhance feed efficiency and reduce eCH_4 emissions in West African cattle systems.

KEYWORDS

emission factors, enteric methane, mitigation, fodder legumes, agropastoral systems, sub-Saharan Africa, zebu cattle



GRAPHICAL ABSTRACT

Highlights

- Peanut and cowpea haulms improved the feed intake and digestibility of zebu cattle.
- Enteric methane yield decreased with increasing rates of legume supplementation.
- Optimal methane reduction was achieved with 75% peanut and 45% cowpea haulm supplementation.
- Legume haulms improve feed protein content and reduce fiber content.

1 Introduction

Ruminants are major contributors to enteric methane (eCH_4) emissions, with cattle alone responsible for nearly 77% of global eCH_4 emissions and 45% of greenhouse gas (GHG) emissions from the livestock sector (Bateki et al., 2023; FAO, 2023).

In West Africa, livestock farming is a vital socioeconomic activity, providing income and employment for households and contributing 10%–13% to the gross domestic product (GDP) of Sahelian countries (FAO, 2019). The predominant system is extensive livestock farming, characterized by seasonal herd movements in search of fodder and water (Gonin, 2018; Sanon et al., 2022). The main challenge facing this system is the pronounced seasonal fluctuation in the availability and quality of rangeland fodder, particularly during the dry season (Assouma et al., 2018). In this context, eCH_4 emissions from ruminants represent the main source of GHG emissions in the livestock sector, accounting for approximately 70% of sectoral emissions and approximately 15% of total anthropogenic GHG emissions in the region (Omotoso and Omotayo, 2024).

Enteric methane (eCH_4) is a potent GHG released by ruminants during their natural digestive process. This emission also represents an energy loss of approximately 2%–12%, which, if recovered or minimized, could enhance livestock productivity (Beauchemin et al., 2020; Popova et al., 2011). Consequently, reducing eCH_4 emissions is a critical strategy for mitigating the climate impact of livestock farming. Lynch et al. (2020) emphasized that lowering methane production to align with its natural atmospheric oxidation rate could significantly reduce global methane concentrations, potentially reversing some effects of climate change.

One of the most effective approaches to reduce eCH_4 emissions is by improving the nutritional quality of ruminant feeds. Enhanced feed formulations can optimize digestion and reduce output per unit of animal product (Arndt et al., 2022; Beauchemin et al., 2020; Eugène et al., 2021; Gerber et al., 2013; Tricarico et al., 2022).

Numerous studies have demonstrated that incorporating fodder legumes into cattle diets significantly improves ration quality while contributing to the reduction of GHG emissions (Baumont et al., 2016; Eugène et al., 2021). These forage species, valued for their high protein content, promote both improved livestock productivity and lower eCH_4 yields, making them a strategic element in sustainable livestock systems (Archimède et al., 2019; Doreau et al., 2016, 2017; Hassen et al., 2017).

In addition to dedicated fodder legumes, crop residues from food legume species, commonly used in mixed farming systems, also contain higher protein levels compared to grasses. These residues play a similarly important role in enhancing feed quality and mitigating eCH_4 emissions, further underscoring the benefits of legume-based feeding strategies (Hassen et al., 2017).

In response to the growing scarcity of natural fodder resources, pastoralists and agropastoralists across West Africa are increasingly turning to feed reserves composed of crop residues and agro-industrial coproducts (Sib et al., 2020; Sodré et al., 2022). Among these, legume haulms are widely utilized as dietary supplements to enhance ration quality and increase livestock productivity (Sib et al., 2018). However, despite their widespread use, the potential of these coproducts to mitigate eCH_4 emissions remains largely underexplored (Hassen et al., 2017; Omotoso and Omotayo, 2024). In this region, haulms from peanut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) are the most commonly used supplements among pastoral and agropastoral communities (Coulibaly, 2012; Gbenou et al., 2024a; Uhder, 2011).

This study contributes to a broader research initiative focused on identifying effective feeding strategies to mitigate eCH_4 emissions from ruminants, with the goal of promoting climate-smart livestock systems in West Africa. It explores the impact of feed supplementation using varying levels of peanut and cowpea haulms on eCH_4 emissions and feed performance, particularly feed intake, in Sudanese Fulani zebu cattle. The objective is to identify optimal inclusion rates for these coproducts that balance enhanced livestock productivity with reduced GHG emissions.

2 Materials and methods

2.1 Study area

This study was conducted in a controlled stall environment at the experimental station of CIRDES (*Centre International de Recherche-Développement sur l'Elevage en zone Subhumide*) located in Bobo-Dioulasso, Burkina Faso. Situated in the western part of the country (11°10′37″ North latitude and 4°17′52″ West longitude), Bobo-Dioulasso lies within the Sudanian climatic zone. The area receives an average annual rainfall of 1,156.4 mm and maintains an average annual temperature of 28.1°C (MEEA, 2024).

2.2 Livestock and fodder

The trial involved 10 Sudanese Fulani zebu bulls, with an average age of 49.0 ± 1.2 and a mean initial body weight (BW) of 183.7 ± 15.9 kg. This breed was selected for its widespread presence across West Africa and its remarkable adaptability to both semiarid and subhumid environments (Nougtara et al., 2021). Characterized by its small size and long horns, the Sudanese Fulani zebu typically reaches an adult BW of 248–300 kg for females and 280–345 kg for males (Ouédraogo et al., 2021). It efficiently utilizes low-quality forage from pastoral rangelands and exhibits strong resistance to heat and drought. Beyond its resilience, the breed plays a multifunctional role in rural economies, serving as a source of meat, milk, leather, hides, manure, and draft power (Hlatshwayo et al., 2023). After 4 months of experimentation, the bulls had reached an average age of 52.8 months and a mean final BW of 209.7 ± 24.7 kg. Throughout the study, the animals were housed individually in 9-m^2 stalls.

The animals were fed a basal diet of *Panicum maximum* cultivar C1 hay, harvested just before the fruiting stage and used as the control feed. This forage was cultivated on the CIRDES farm located in the village of Banakélédaga, approximately 15 km from Bobo-Dioulasso, within the Bama commune (Bama commune, 11°23′59″N and 4°25′46″W). Haulms of peanut (*A. hypogaea*) and cowpea (*V. unguiculata*) were incorporated into the basal diet as nutritional supplements to enhance feed quality. The haulms were collected in a single batch from local farmers operating on the outskirts of Bobo-Dioulasso, thereby ensuring consistency in feed quality throughout the trial.

2.3 Experimental design

A total of 11 feeding trials were conducted, corresponding to the number of experimental diets evaluated. Each trial spanned 21 days, comprising a 14-day adaptation phase followed by a 7-day data collection period. Initially, all 10 animals were administered a control diet consisting exclusively of *P. maximum* C1, designated as P100. To facilitate simultaneous evaluation of both legume haulms, the animals were randomly assigned to two groups of five. The first group received diets combining *P. maximum* with peanut (*A. hypogaea*) haulms at inclusion ratios of 85:15 (A15), 70:30 (A30), 55:45 (A45), 40:60 (A60), and 25:75 (A75). The second group was offered diets incorporating *P. maximum* with cowpea (*V. unguiculata*) haulms in identical proportions: 85:15 (N15), 70:30 (N30), 55:45 (N45), 40:60 (N60), and 25:75 (N75) (Figure 1).

The experimental rations were administered in a randomized sequence based on legume inclusion levels: 15%, 45%, 60%, 75%, and 30%, followed by the control diet (100% *P. maximum*). This design aimed to minimize the carryover effects associated with the control diet, which is characterized by low nutritive value, particularly in terms of protein content. For the control diet (P100) and diets containing 15% to 45% legume haulms (A15 to A45 and N15 to N45), the total daily feed allowance was set at 2.5% of each animal's BW. For diets with higher inclusion levels (A60, A75, N60, and N75), the feed quantity was increased to 3% of BW to accommodate elevated intake levels observed during preliminary trials. This feeding strategy was designed to ensure a minimum refusal rate of 10%, thereby enabling accurate assessment of voluntary intake. Rations were distributed in two equal portions: the first at 8:30 a.m. and the second at 4:30 p.m., in accordance with traditional cattle-feeding practices in the region, where supplements are typically provided at these times. Throughout the trial, animals had *ad libitum* access to clean drinking water via individual rubber water troughs, as well as mineral licking stones.

2.4 Chemical composition

For each trial, daily samples were collected, labeled, and weighed for the offered ration (n_1 = 7), individual feed refusals

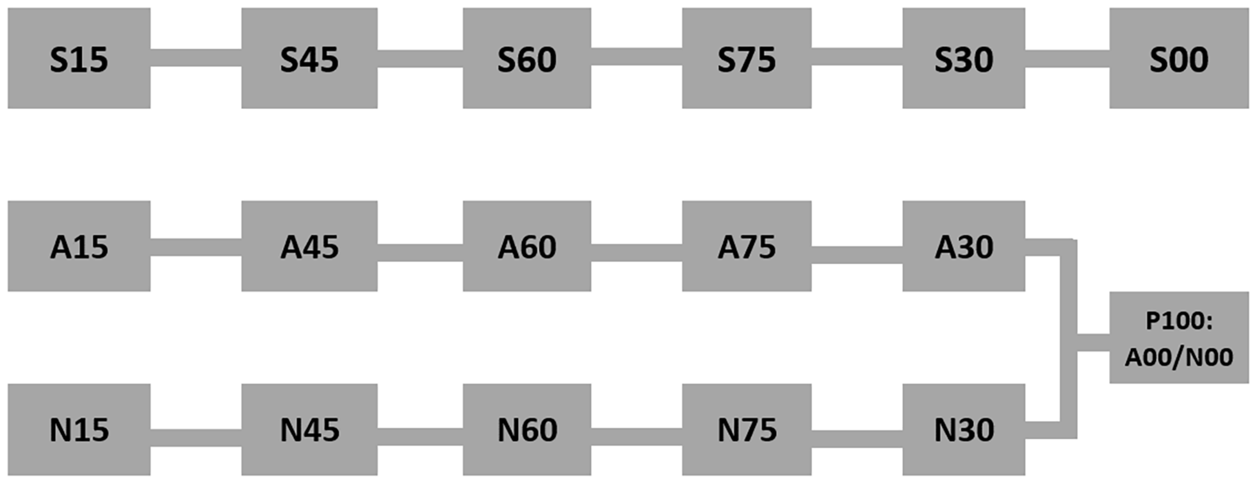


FIGURE 1
Chronological experimental design for feeding Sudanese Fulani zebu cattle. A15: *P. maximum* + *A. hypogaea* (85:15), A45: *P. maximum* + *A. hypogaea* (55:45), A60: *P. maximum* + *A. hypogaea* (40:60), A75: *P. maximum* + *A. hypogaea* (25:75), A30: *P. maximum* + *A. hypogaea* (70:30) P100: A00/N00: 100% *Panicum maximum* C1 N15: *P. maximum* + *V. unguiculata* (85:15), N45: *P. maximum* + *V. unguiculata* (55:45), N60: *P. maximum* + *V. unguiculata* (40:60), N75: *P. maximum* + *V. unguiculata* (25:75), N30: *P. maximum* + *V. unguiculata* (70:30).

(n_2 = 70 for the control ration and n_2 = 35 for each experimental ration), and individual feces (n_3 = 70 for the control ration and n_3 = 35 for each experimental ration). All samples were oven-dried at 55°C for 72 h, reweighed to determine dry matter content, and subsequently ground using a Retsch mill (SM 100 model, Retsch GmbH, Haan, Germany) equipped with a 1-mm sieve. In total, 77 samples of offered feed, 420 samples of refusals, and 420 fecal samples were collected and processed for further analysis.

The chemical composition of feed and feces samples was determined using near-infrared spectrometry (NIRS). Ground samples were scanned at CIRDES using a Bruker FTIR spectrometer (Tango model, Bruker Optics, Bremen, Germany), which captures spectra in the range of 11,536 to 3,952 cm^{-1} with an 8-cm^{-1} resolution step. Each sample was placed into a scanning cup and scanned three times consecutively. The resulting spectrum for each sample was averaged across the three scans to ensure consistency and accuracy. Spectral data were used to predict the following parameters: dry matter (DM), ash, crude protein (CP), crude fiber (CF), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and *in vitro* digestibility of organic (IVDOM) and dry matter (IVDMD). These predictions were calibrated using reference benchmarks developed by the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), based on a database of 1,890 forage samples and 690 fecal samples. Calibration models were further validated and updated through reference analyses conducted on samples from the present study.

The reference analytical methods used to validate NIRS predictions were as follows: residual DM determined by oven-drying samples at 103°C for 24 h; ash content measured after calcination at 550°C for 4 h; CP content determined using the Kjeldahl method, with nitrogen content multiplied by a conversion factor of 6.25; CF determined using the Weende method; and fiber fractions (NDF, ADF) and ADL determined using the Van Soest sequential method.

2.5 Feed intake, apparent digestibility, and gross energy

To ensure accurate measurement of eCH_4, pelleted bait composed of 90% rangeland grass and 10% molasses was used to maintain the animals' head position within the GreenFeed system during measurements. The quantity of bait consumed by each animal was recorded daily and subsequently incorporated into the calculation of total daily DM intake per animal. This intake was computed using Equation 1:

$$\begin{aligned} &Dry\ \ matter\ \ intake \\ &\quad = Offered\ \ (diet + bait) - Refusals\ \ (diet + bait) \end{aligned} \tag{1}$$

The intake of additional chemical components, including organic matter (OMi), crude protein (CPi), crude fiber (CFi), neutral detergent fibers (NDFi), acid detergent fibers (ADFi), and acid detergent lignin (ADLi), was estimated based on the chemical composition of offered feed and refusals.

To determine DM apparent digestibility (DMd), feces from each animal were collected and weighed daily throughout the data collection period. DMd was subsequently calculated using Equation 2:

$$DMd = \frac{DM\ \ intake - Faeces\ \ DM\ \ excreted}{DM\ \ intake} * 100 \tag{2}$$

The apparent digestibility of other chemical components, including organic matter (OMd), crude protein (CPd), crude fiber (CFd), neutral detergent fiber (NDFd), and acid detergent fiber

(ADFd), was determined using the same method applied for dry matter, based on the difference between intake and fecal output.

Gross energy (GE) values of the rations were calculated using Equation 3, in accordance with the methodology recommended by INRA (2018).

$$GE = (4531 + 1,735 * CP + \Delta) * \frac{OM}{1000} \quad (3)$$

GE = Gross energy (kcal), OM = organic matter (g/kg DM), CP = crude protein (g/kg OM), Δ = constant, with Δ = 82 for hay.

An extrapolation to a hypothetical 100% legume haulm inclusion level was performed to estimate DM intake and apparent digestibility coefficients, including DMd, OMd, CFd, NDFd, and ADFd.

2.6 Enteric methane emission measurements

Direct measurements of eCH_4 emissions were conducted using the GreenFeed system (ID 252, C-Lock, Inc., Rapid City, SD, USA). Each animal was equipped with a microchip to enable individual identification and data collection by the system. On average, animals spent 3 min 16 s ± 26 s per visit in the GreenFeed unit (range: 2 min 1 s to 7 min 56 s). To maintain head positioning during sampling, 31.5 g of bait was dispensed at 1-min intervals into the feeder.

eCH_4 emissions were recorded six times daily, at 6:30 a.m., 10:00 a.m., 2:00 p.m., 6:00 p.m., 9:00 p.m., and 0:00 a.m., aligned with the animals' feeding and rumination patterns. The 6:30 a.m. measurement followed an overnight fast, while the 10:00 a.m. and 6:00 p.m. readings occurred after the morning (8:30 a.m.) and evening (4:30 p.m.) feedings. The 2:00 p.m. measurement coincided with a resting and rumination period, and nighttime readings were taken at 9:00 p.m. and midnight.

Measurements taken at 10:00 a.m., 2:00 p.m., and 6:00 p.m. were classified as daytime emissions (eCH_4d), whereas those at 9:00 p.m., 0:00 a.m., and 6:30 a.m. were categorized as nighttime emissions (eCH_4n). Each animal completed 42 visits to the GreenFeed unit per trial, surpassing the minimum recommended threshold of 20 measurements per animal over a 7–14-day period with a 14–21-day adaptation phase for reliable data collection (Hristov et al., 2015; Manafiazar et al., 2016). Across the 11 trials, a total of 2,492 valid GreenFeed measurements were obtained from 2,560 attempted readings, yielding a success rate of 97.37%. After removing outliers (1.08%) using the linear regression method described by Coppa et al. (2021), the final dataset comprised 2,465 measurements for analysis.

Average daily eCH_4 emissions (g/day) per animal were calculated using Equation 4.

$$eCH_4 \ (g/d) = \frac{\sum(eCH_4d) + \sum(eCH_4n)}{6} \quad (4)$$

where eCH_4d and eCH_4n represent daytime and nighttime eCH_4 measurements, respectively.

In addition to eCH_4, carbon dioxide (CO_2) emissions were also measured. The GreenFeed unit was automatically calibrated daily at 4:00 a.m., outside the measurement periods, using a certified gas mixture containing CH_4 (0.509 ppmv), CO_2 (4.993 ppmv), H_2 (0.010 ppmv), and O_2 (0.021 ppmv) supplied by Air Liquide and C-Lock Inc. (USA). To ensure system accuracy, a CO_2 recovery test was conducted at both the beginning and end of each trial, and the unit's filter was replaced whenever airflow dropped below 27 L/s (Gbenou et al., 2024b). During the experimental period, key operational parameters were monitored and recorded. The average CO_2 flux was 2,524 ± 513.9 g/day (min = 1,424.6, max = 5045.9), airflow speed averaged 34.8 ± 3.9 L/s (min = 23.2, max = 39.4), and wind direction averaged 125.9 degrees (min = 1.1, max = 357.6).

To estimate eCH_4 and CO_2 emissions at a hypothetical 100% legume haulm inclusion rate, extrapolations were performed using regression models. These models enabled the prediction of daily emissions as well as emissions normalized per unit of BW.

2.7 Statistical analysis

Statistical analyses were performed using R software version 3.6.0 (R Core Team, 2023). Data were assessed for normality using the Shapiro–Wilk test (Villasenor Alva and Gonzalez-Estrada, 2009) and for homogeneity of variances using Levene's test (Gozde and Osman, 2024), both at a 5% significance level. Analysis of variance (ANOVA) was performed to evaluate the effect of legume haulm inclusion rates on ration chemical composition, feed intake, digestibility parameters, and eCH_4 emissions. The chemical composition of the offered diet was analyzed using one-way ANOVA, considering the factor diet. All the other variables were analyzed using a two-way ANOVA, with diet and animal as fixed factors. In case the assumption of normality and/or homogeneity of variance were not met, the Kruskal–Wallis test was applied as a non-parametric alternative. Mean comparisons were conducted using Dunn's test for the following parameters: CP, CF, and NDF content in refusals; CF and NDF intake; and CP digestibility.

Means for all response variables analyzed were compared using the Newman–Keuls *post hoc* test. ANOVA was performed separately for the two animal groups (peanut haulms and cowpea haulms) as the animals differed between groups. Additionally, after verifying the assumptions of linearity, independence, homoscedasticity, and normality, linear regression analyses were applied to assess the relationships between legume haulm inclusion rates and dry matter intake, digestibility coefficients, and gas emissions.

3 Results

3.1 Chemical composition and gross energy

Peanut and cowpea haulms exhibited OM contents of 89.2% and 93.5% of DM, respectively (Table 1). Both haulms contained CP levels exceeding 13% DM, CF contents below 26% DM, NDF contents below 43% DM, and ADF contents below 29% DM. In contrast, *P. maximum* hay presented a slightly higher OM content (94% DM), but a markedly lower CP content (4.1% DM), along with substantially higher fiber fractions compared to the legume haulms.

Supplementation with legume haulms significantly reduced the OM content of the rations ($p < 0.05$). Specifically, a 30% inclusion of peanut haulms resulted in a 2.3% reduction, while a 45% inclusion of cowpea haulms led to a 1.8% decrease. Ration supplementation also induced significant declines in CF, ADF, and NDF contents ($p < 0.01$), with reductions of approximately 10, 25, and 10 percentage points, respectively, relative to the control *Panicum* hay. In contrast, CP content increased significantly and progressively with higher levels of haulm inclusion ($p < 0.01$), reaching 10.9% DM and 11.5% DM in rations containing 75% peanut and cowpea haulms, respectively, representing an increase of over 168% compared to the control. However, lignin content (ADL) also rose significantly ($p < 0.01$) by 49% and 33% with peanut and cowpea haulm inclusion, respectively.

Regardless of the legume type used for supplementation, the chemical composition of feed refusals exhibited trends consistent with those observed in the offered rations. However, refusals consistently exhibited lower CP contents and elevated levels of fiber and lignin. Specifically, CP contents in refusals declined by 25% to 45% relative to the corresponding offered rations, while fiber contents increased by 3.5% to 31%. For the offered rations, GE content, initially 18.4 MJ/kg DM for the control diet (*P. maximum* hay only), increased significantly with legume haulm supplementation. At the highest inclusion level (75%), GE values reached 18.7 MJ/kg DM with peanut haulms and 19.1 MJ/kg DM with cowpea haulms. In contrast, the GE content of refusals from the control ration averaged 18.6 MJ/kg DM. With increasing levels of legume haulm inclusion (0% and 45%), GE content in refusals declined significantly and progressively.

3.2 Feed intake

Dry matter intake (DMi), which averaged 3.82 kg/day under the control ration (P100), increased with the inclusion of legume haulms. Specifically, DMi rose by 0.3% to 28.9% with peanut haulms and by 6.5% to 27.9% with cowpea haulms, depending on the inclusion level. Supplementation also resulted in a marked reduction in feed refusal rates (Figure 2). While refusals averaged 29% under the control ration, they declined to approximately 15% at higher inclusion levels (60% and 75%). Extrapolation to a hypothetical 100% legume haulm diet yielded estimated daily intakes of 5.18 kg for peanut haulms and 5.31 kg for cowpea haulms (Figure 3). When expressed relative to BW, DMi for the control ration was 19 g/kg BW in the peanut-supplemented group and 17.5 g/kg BW in the cowpea-supplemented group. These values increased by 12.1% to 48.9% and 14.8% to 30.1%, respectively, across supplementation levels ranging from 15% to 75%.

Crude protein intake (Cpi) increased sharply with rising levels of legume haulm inclusion. Between 15% and 75% inclusion, CPi increased by 36% to 142% with peanut haulms and by 38% to 169% with cowpea haulms ($p < 0.001$) (Table 2). A similar upward trend was observed for lignin intake. In contrast, intakes of CF, NDF, and ADF declined progressively with increasing supplementation levels. Overall, total feed intake increased by 17.8% to 49% across the 15% to 75% inclusion range ($p < 0.001$). Gross energy intake (GEi), initially measured at 18.3 MJ/kg DM for the control diet, also rose significantly with supplementation, reaching a 3.2% increase at the 75% legume haulm inclusion level.

3.3 Apparent digestibility

For *P. maximum* hay, the average DMd was 50.3% ± 4%. However, a difference exceeding 3.5 percentage points was observed between the two animal groups (Table 3). Gradual incorporation of legume haulms into the rations resulted in a 5%–10% increase in DMd, although this improvement reached statistical significance ($p < 0.05$) only with cowpea haulm supplementation. A similar trend was observed for OMd, with values ranging from 50.2% to 59.4%.

Crude protein digestibility (CPd) increased significantly with haulm supplementation ($p < 0.01$), particularly between 0% and 30% inclusion levels. However, at higher supplementation rates (60% and 75%), CPd gains were smaller and did not reach statistical significance. In contrast, CFd, NDFd, and ADFd declined significantly with increasing legume haulm inclusion ($p < 0.05$).

Regression analyses revealed a linear relationship between haulm inclusion rates and digestibility parameters including DMd, OMd, CFd, NDFd, and ADFd (Figures 4, 5). Extrapolation to a hypothetical 100% haulm-based diet predicted digestibility values of 56.4% (DMd), 60.3% (OMd), 52.4% (CFd), 46.1% (NDFd), and 40.2% (ADFd) for peanut haulms and 57.6%, 62.8%, 46.5%, 45.8%, and 41.2%, respectively, for cowpea haulms. In contrast, the relationship between haulm inclusion level and CPd did not follow a linear trend.

3.4 Enteric methane emissions

Supplementation with legume haulms, irrespective of type, resulted in increased eCH_4 emissions (g/day). In batch 1, where animals were fed rations supplemented with peanut haulms, daily emissions increased by 13% to 17% relative to the control diet (95.6 ± 12.6 g/day). In batch 2, where the control ration yielded 103 ± 7 g/day, cowpea haulm supplementation led to a more pronounced increase in emissions, ranging from 16% to 29% ($p < 0.05$). When normalized to body weight (g/kg BW), eCH_4 emissions for the control diet averaged 0.48. With supplementation levels between 30% and 75%, emissions increased by 19% and 40% for peanut haulms and by 21% to 45% for cowpea haulms (Table 4).

Energy yield (Ym), expressed as a percentage of GEi, declined significantly with increasing levels of peanut haulm supplementation ($p < 0.05$), averaging 8.3% ± 0.3% GEi. In contrast, Ym remained statistically unchanged with cowpea haulm inclusion. The eCH_4 yield, expressed in grams per kilogram of dry matter intake (g/kg DMi), was

TABLE 1 Chemical composition (in % DM) and gross energy (MJ/kg DM) of offered diets and refusals from Fulani zebu cattle fed increasing quantities of peanut and cowpea haulms.

Treatment	Offered diet							Refusals						
	OM (% DM)	CP (% DM)	CF (%DM)	NDF (% DM)	ADF (% DM)	ADL (% DM)	GE (MJ/kg DM)	OM (% DM)	CP (% DM)	CF (% DM)	NDF (% DM)	ADF (% DM)	ADL (% DM)	GE (MJ/kg DM)
Peanut haulms	89.2	14.0	24.9	42.1	28.6	8.8	18.2	–	–	–	–	–	–	–
Cowpea haulms	93.5	13.4	25.6	40.5	28.2	7.3	19.0	–	–	–	–	–	–	–
A00*	93.9^{a}	4.1^{c}	41.5^{a}	78.9^{a}	47.9^{a}	6.5^{c}	18.4^{b}	95.3^{a}	2.9^{d}	44.5^{a}	81.7^{a}	51.3^{a}	8.1^{bc}	18.6^{a}
A15	94.1^{a}	6.0^{b}	38.3^{b}	74.0^{b}	44.6^{b}	6.5^{c}	18.6^{a}	94.5^{ab}	4.1^{bc}	42.5^{b}	78.5^{a}	49.1^{bc}	7.9^{c}	18.5^{a}
A30	91.7^{c}	6.7^{b}	37.5^{b}	66.9^{c}	43.3^{b}	8.2^{b}	18.2^{c}	93.8^{bc}	3.5^{cd}	45.1^{a}	78.9^{a}	50.7^{ab}	8.6^{b}	18.4^{b}
A45	92.9^{b}	9.5^{a}	33.5^{c}	61.6^{d}	39.6^{c}	7.5^{bc}	18.6^{a}	93.0^{c}	4.5^{b}	39.6^{c}	67.4^{c}	46.0^{d}	10.0^{a}	18.3^{b}
A60	93.3^{ab}	9.9^{a}	33.2^{c}	57.0^{e}	39.1^{c}	8.3^{b}	18.7^{a}	94.6^{ab}	4.5^{b}	41.7^{b}	73.9^{b}	48.2^{c}	8.7^{b}	18.6^{a}
A75	92.9^{b}	10.9^{a}	30.0^{d}	50.3^{f}	36.3^{d}	9.7^{a}	18.7^{a}	94.0^{bc}	6.0^{a}	38.5^{c}	66.3^{c}	45.1^{d}	9.8^{a}	18.6^{a}
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
N00*	93.9^{B}	4.1^{D}	41.5^{A}	78.9^{A}	47.9^{A}	6.5^{B}	18.4^{C}	94.9^{A}	3.2^{E}	43.9^{A}	81.2^{A}	50.6^{A}	7.9^{B}	18.6^{B}
N15	93.4^{BC}	6.1^{C}	38.6^{AB}	73.5^{A}	44.4^{AB}	6.4^{B}	18.5^{C}	94.2^{B}	4.4^{C}	42.3^{B}	78.1^{B}	48.9^{B}	8.1^{B}	18.5^{B}
N30	92.8^{BC}	6.8^{BC}	37.7^{AB}	67.0^{B}	42.1^{BC}	6.9^{B}	18.4^{C}	93.9^{B}	3.9^{D}	44.7^{A}	78.2^{B}	50.2^{A}	8.6^{B}	18.4^{C}
N45	92.3^{C}	8.2^{B}	34.7^{BC}	59.6^{C}	39.7^{C}	8.4^{A}	18.4^{C}	92.8^{C}	4.5^{C}	39.5^{C}	65.7^{D}	45.7^{C}	10.4^{A}	18.2^{D}
N60	95.1^{A}	10.7^{A}	31.3^{C}	54.4^{CD}	34.9^{D}	6.7^{B}	19.1^{A}	94.3^{B}	5.5^{B}	40.5^{C}	71.0^{C}	46.6^{C}	8.3^{B}	18.6^{AB}
N75	93.5^{BC}	11.5^{A}	31.1^{C}	52.2^{D}	35.5^{D}	8.7^{A}	18.9^{B}	94.4^{AB}	6.0^{A}	40.4^{C}	65.8^{D}	46.3^{C}	10.3^{A}	18.7^{A}
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	0.001	<0.001	<0.01	<0.001	<0.001

A00, A15, A30, A45, A60, and A75: peanut haulm incorporation levels at 0%, 15%, 30%, 45%, 60%, and 75%, respectively. N00, N15, N30, N45, N60, and N75: cowpea haulms incorporated at 0%, 15%, 30%, 45%, 60%, and 75%, respectively. Values with the same letter in each column do not differ significantly at the 5% level.
OM, organic matter; CP, crude protein; *N00 and A00, pure *Panicum* hay; DM, dry matter; CF, crude fiber; NDF, neutral detergent fiber; ADF, acid detergent fiber; ADL, acid detergent lignin; GE, gross energy.

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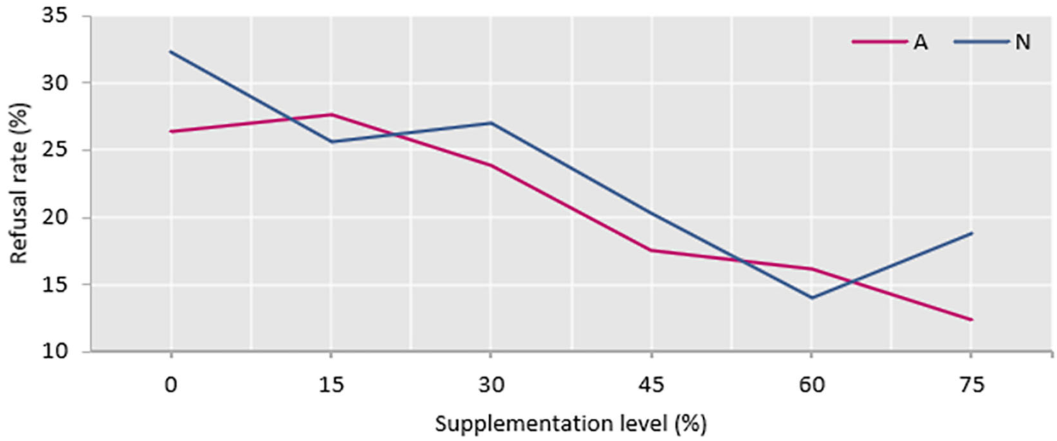

FIGURE 2
Refusal rate in Sudanese Fulani zebu bulls supplemented with peanut (A) and cowpea (N) haulms at various rates.

26.2 ± 1.4 g for the control ration. This value decreased significantly by 6.1% at 75% peanut haulm supplementation and by 4.75% at 45% cowpea haulm supplementation. However, at lower supplementation levels (15%), eCH_4 yield increased by 17.9% with peanut haulms and by 5% with cowpea haulms.

Regression analyses revealed linear relationships for daily eCH_4 output, emissions per unit of body weight (g/kg BW), and energy yield (Ym), enabling extrapolation. At a hypothetical 100% haulm supplementation level, predicted values were 124.2 g eCH_4/day, 0.73 g/kg BW, and 7.4% GEi for peanut haulms and 135.5 g eCH_4/day, 0.74 g/kg BW, and 7.7% GEi for cowpea haulms (Figures 6, 7, 8).

4 Discussion

4.1 Chemical composition

The control ration, composed exclusively of *P. maximum* hay, exhibited a high OM content of 94% DM, closely aligning with the 93.9% DM reported by Sana (2015) for *Panicum* harvested at the flowering stage. However, its CP content was notably low (4.1% DM), consistent with the values observed for *Panicum* at maturity (Sana, 2015) and with data collected by Gbenou et al. (2024b) for rangeland fodder during the cool dry season in the study area. The

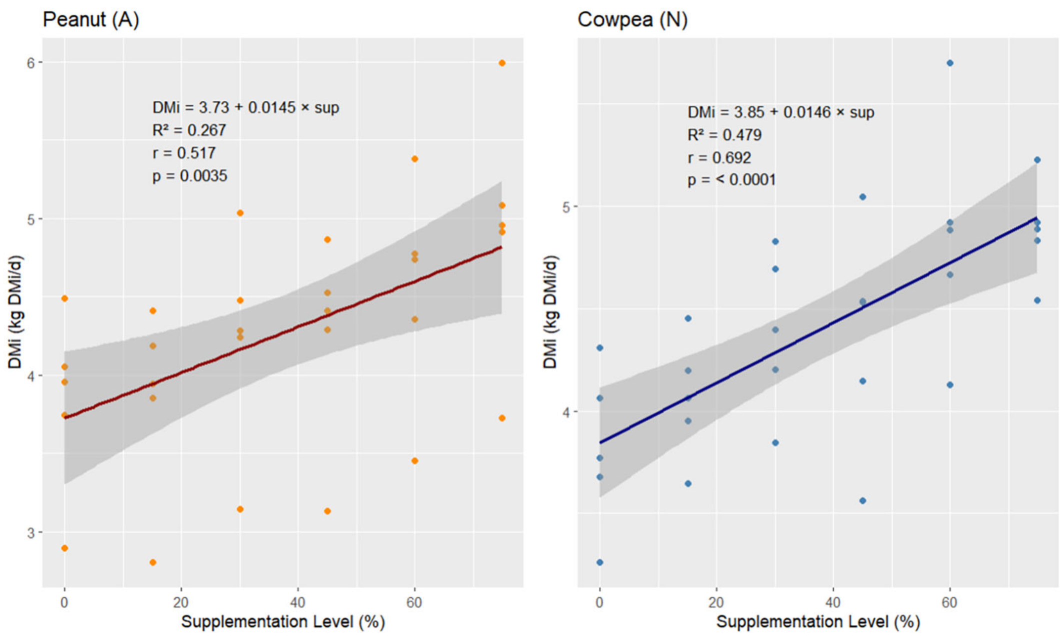

FIGURE 3
Regression lines for DM intake by incorporation levels of peanut (A) and cowpea (N) haulms.

TABLE 2 Feed intake by Fulani zebu cattle fed increasing quantities of peanut and cowpea haulms.

Treatment	DMi (kg/day)	DMi (g/kg BW)	OMi (% DM)	CPi (% DM)	CFi (% DM)	NDFi (% DM)	ADFi (% DM)	ADLi (% DM)	GEi (MJ/kg DM)
A00	3.8[c]	19.0[e]	93.3[a]	4.5[e]	39.9[a]	76.9[a]	46.2[a]	5.9[d]	18.3[c]
A15	3.8[c]	21.3[d]	93.5[a]	6.1[d]	37.4[b]	71.9[b]	43.5[b]	6.4[d]	18.5[b]
A30	4.2[b]	22.1[cd]	90.9[c]	7.5[c]	34.9[c]	62.5[c]	40.9[c]	8.1[b]	18.1[d]
A45	4.2[b]	23.3[c]	92.3[b]	9.6[b]	33.1[d]	61.3[c]	39.1[d]	7.2[c]	18.5[b]
A60	4.5[b]	25.5[b]	92.6[b]	10.5[a]	31.7[e]	54.1[d]	37.5[e]	8.3[b]	18.6[a]
A75	4.9[a]	28.3[a]	92.4[b]	10.8[a]	29.6[f]	49.7[e]	36.0[f]	9.6[a]	18.6[a]
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N00	3.8[D]	17.5[C]	93.3[B]	4.5[E]	39.9[A]	76.9[A]	46.1[A]	5.8[B]	18.3[C]
N15	4.1[C]	21.7[B]	92.9[B]	6.2[D]	37.7[B]	71.7[B]	43.4[B]	6.3[B]	18.4[C]
N30	4.4[B]	21.1[B]	92.1[C]	7.7[C]	34.9[C]	62.1[C]	39.0[C]	6.4[B]	18.3[C]
N45	4.4[B]	22.1[B]	91.8[C]	8.5[B]	34.0[C]	58.9[D]	38.9[C]	8.0[A]	18.3[C]
N60	4.9[A]	25.3[A]	94.9[A]	11.3[A]	30.1[D]	52.1[E]	33.5[D]	6.6[B]	19.1[A]
N75	4.9[A]	26.0[A]	93.1[B]	12.0[A]	29.8[D]	50.4[E]	34.1[D]	8.4[A]	18.9[B]
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

A00, A15, A30, A45, A60, and A75: peanut haulm incorporation levels at 0%, 15%, 30%, 45%, 60%, and 75%, respectively. N00, N15, N30, N45, N60, and N75: cowpea haulms incorporated at 0%, 15%, 30%, 45%, 60%, and 75%, respectively. A00 and N00: pure *Panicum* hay. Values with the same letter in each column do not differ significantly at the 5% level.
DMi, dry matter intake; OMi, organic matter intake; CPi, crude protein intake; CFi, crude fiber intake; NDF, neutral detergent fiber intake; ADF, acid detergent fiber intake; ADL, acid detergent lignin intake; GEi, gross energy intake.

TABLE 3 Apparent digestibility of chemical components in Fulani zebu cattle fed increasing quantities of peanut and cowpea haulms.

Treatment	DMd (%)	OMd (%)	CPd (%)	CFd (%)	NDFd (%)	ADFd (%)
A00*	52.1	54.0[b]	18.9[d]	61.4[a]	61.8[a]	57.0[a]
A15	52.3	55.0[ab]	40.1[c]	60.1[a]	61.3[a]	56.3[a]
A30	53.6	54.7[ab]	54.0[b]	57.9[ab]	55.3[b]	51.4[b]
A45	54.2	57.5[ab]	60.2[ab]	58.2[ab]	57.4[b]	51.9[b]
A60	54.8	57.7[ab]	63.0[a]	55.9[b]	51.1[c]	46.7[c]
A75	55.0	58.6[a]	64.2[a]	54.4[b]	50.4[c]	44.1[c]
A100**	56.4	60.3	(85.9)	52.4	46.1	40.2
p-value	0.318	0.013	<0.001	<0.001	<0.001	<0.001
N00*	48.5[B]	50.2[C]	02.9[C]	57.7[AB]	58.3[A]	53.1[A]
N15	52.8[A]	55.0[B]	42.4[B]	59.5[A]	61.5[A]	56.8[A]
N30	52.4[A]	53.6[B]	57.2[A]	53.2[BC]	53.0[B]	48.4[BC]
N45	53.6[A]	56.2[AB]	57.5[A]	55.9[AB]	52.6[B]	51.4[B]
N60	54.4[A]	59.0[A]	66.6[A]	50.2[C]	50.5[B]	44.2[C]
N75	55.3[A]	59.4[A]	71.1[A]	49.5[C]	50.5[B]	45.4[C]
N100**	57.6	62.8	(98.9)	46.5	45.8	41.2
p-value	<0.004	<0.001	<0.001	<0.001	<0.001	<0.001

A00, A15, A30, A45, A60, and A75: peanut haulm incorporation levels at 0%, 15%, 30%, 45%, 60%, and 75%, respectively. **A100: extrapolation to 100% peanut haulm supplementation. N00, N15, N30, N45, N60, and N75: cowpea haulm incorporation levels at 0%, 15%, 30%, 45%, 60%, and 75% respectively. *A00 and N00: pure *Panicum* hay. **N100: extrapolation to 100% cowpea haulm supplementation. According to the columns, the values assigned the same letter do not differ significantly at the 5% level.
DMd, dry matter digestibility; OMd, organic matter digestibility; CPd, crude protein digestibility; CFd, crude fiber digestibility; NDFd, neutral detergent fiber digestibility; ADFd, acid detergent fiber digestibility.

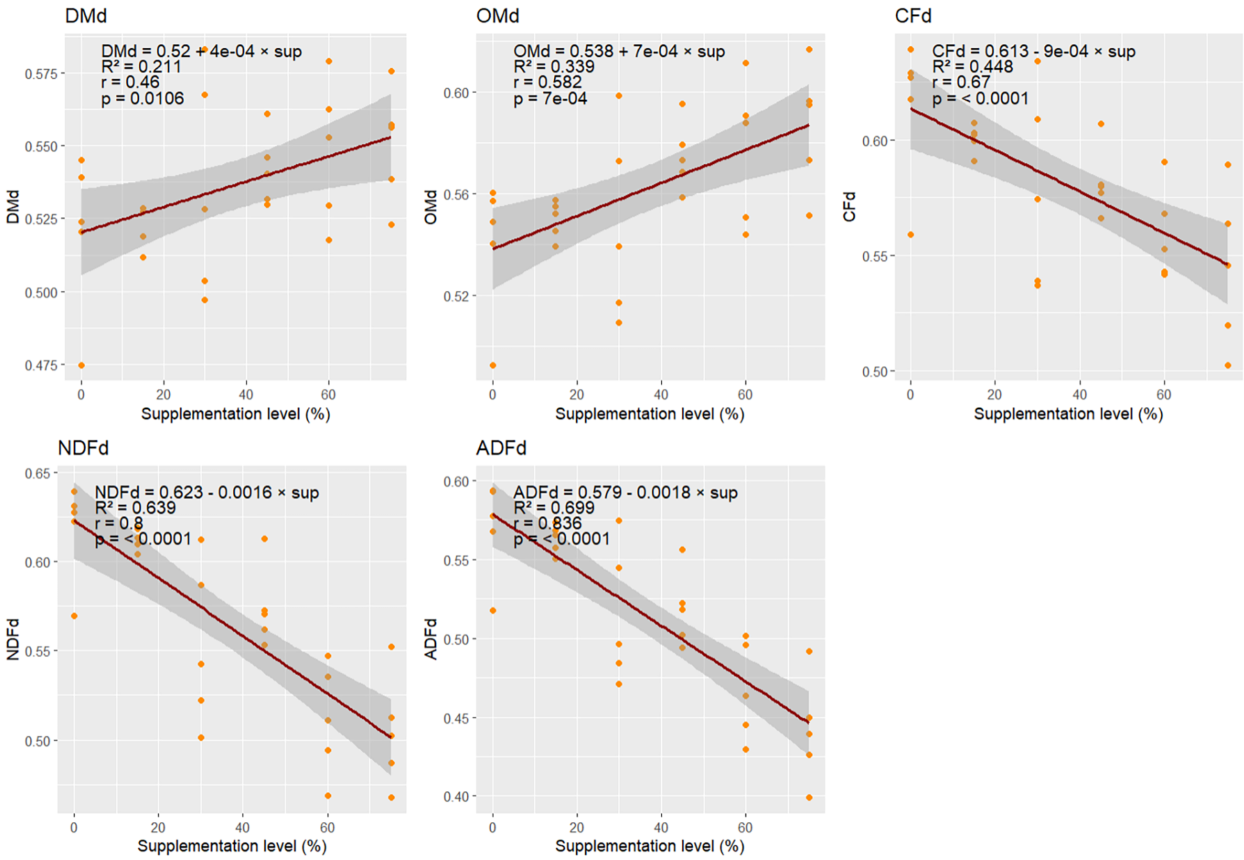

FIGURE 4
Regression lines for peanut haulm digestibility.

cool dry season is characterized by residual nutritional value in rangeland fodder and the availability of crop residues in fields, making a transitional phase in forage quality. The hay used in this study, harvested during the hot dry season, represented relatively high-quality rangeland fodder, as typical CP contents during this period fall below 3% DM (Gbenou et al., 2024b; Millogo et al., 2019).

The control ration also exhibited very high fiber concentrations, comparable to late-harvested *Panicum* described by Sana (2015), which had NDF and ADF contents of 80.7% and 49.4% DM, respectively. In contrast, the peanut and cowpea haulms used as supplements demonstrated markedly superior nutritional profiles. Both haulms contained CP levels exceeding 13% DM and significantly lower fiber fractions, making them valuable feed resources for improving ration quality.

This study confirms that supplementing cattle rations with herbaceous legume haulms improves their chemical composition. CP content, a key determinant of the nutritional value of tropical forage crops (Archimède et al., 2019), increased with supplementation, while fiber fractions (CF, NDF, and ADF) declined as legume haulm inclusion levels rose. This inverse relationship between CP and total plant cell wall content (NDF), previously reported by Barbosa et al. (2018), reflects the fundamental botanical distinction between legumes and grasses: legumes are generally richer in protein and poorer in structural carbohydrates (Baumont et al., 2016). Thus, the incorporation of peanut and cowpea haulms into *P. maximum* hay-based rations enhanced overall feed value by improving protein supply and reducing indigestible fiber content. Additionally, the GE values recorded in this study for both offered rations and refusals were consistent with the regional average of 18.4 MJ/kg DM, commonly used in forage energy calculations for Sub-Saharan Africa (Bateki et al., 2023). These values were notably higher than the 17.4 MJ/kg DM reported by Gbenou et al., (2024b) for rangeland fodder harvested during the hot dry season, which is characterized by low nutritional quality.

4.2 Feed intake

The average daily DM intake for the control diet was 3.8 kg/day for both animal batches. When expressed relative to BW, intake amounted to 19 g/kg BW for batch 1 and 17.5 g/kg BW for batch 2. This difference reflects the initial disparity in body weight between the two groups, with batch 2 animals, assigned to cowpea haulm trials, weighing on average 8 kg more than batch 1 animals, which were assigned to the peanut haulm trials. These intake values exceed those reported by Gbenou et al., (2024b) for the hot dry season (15.7 g/kg

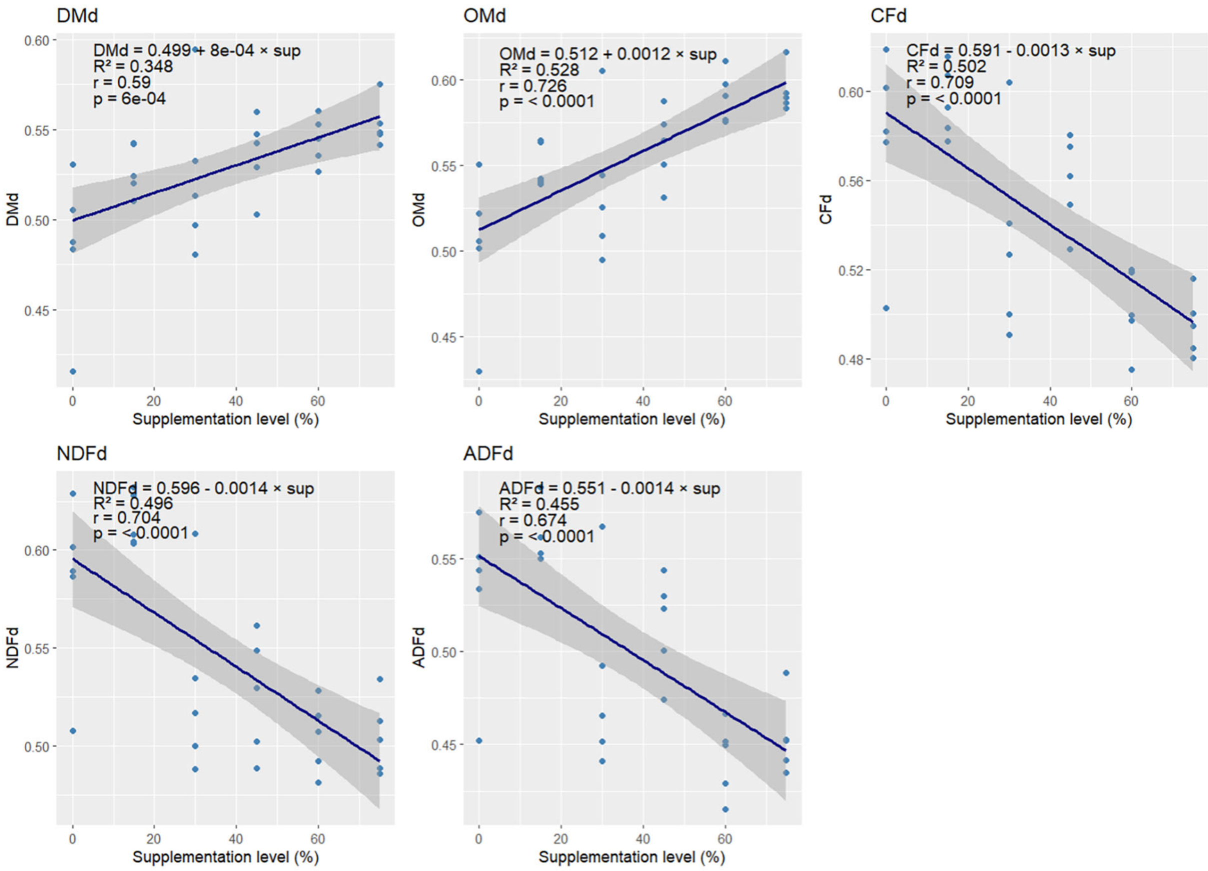

FIGURE 5
Regression lines for cowpea haulm digestibility.

TABLE 4 Enteric methane emissions from Fulani zebu cattle fed increasing quantities of peanut and cowpea haulms.

Treatment	eCH_4 (g/day)	eCH_4 (g/kg BW)	eCH_4 (g/kg DMi)	eCH_4 (g/kg OM)	eCH_4 (MJ/day)	Ym (% GEi)
A00	95.6^{b}	0.48^{d}	25.3^{bc}	26.9^{bc}	5.3^{b}	7.7^{bc}
A15	112.3^{a}	0.63^{b}	29.8^{a}	31.5^{a}	6.2^{a}	9.0^{a}
A30	109.1^{a}	0.57^{c}	26.0^{b}	28.4^{b}	6.1^{a}	8.1^{b}
A45	112.2^{a}	0.62^{b}	26.8^{b}	28.9^{b}	6.2^{a}	8.3^{b}
A60	115.5^{a}	0.65^{ab}	25.5^{bc}	27.5^{bc}	6.4^{a}	7.9^{bc}
A75	116.5^{a}	0.67^{a}	23.7^{c}	25.6^{c}	6.5^{a}	7.3^{c}
p-value	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N00	103.0^{C}	0.47^{C}	27.2^{AB}	29.0^{AB}	5.7^{C}	8.3^{AB}
N15	115.4^{B}	0.62^{B}	28.6^{A}	30.7^{A}	6.4^{B}	8.8^{A}
N30	120.7^{AB}	0.58^{B}	27.7^{AB}	29.9^{AB}	6.7^{AB}	8.6^{AB}
N45	112.3^{B}	0.57^{B}	25.9^{B}	28.2^{B}	6.2^{B}	8.1^{BC}
N60	126.9^{A}	0.66^{A}	26.2^{B}	27.5^{B}	7.1^{A}	7.9^{C}
N75	127.7^{A}	0.68^{A}	26.3^{B}	28.1^{B}	7.1^{A}	8.1^{BC}
p-value	<0.001	<0.001	<0.014	<0.001	<0.001	<0.001

eCH_4, enteric methane; DMi, dry matter intake; BW, body weight; OM, organic matter; Ym, energy yield; GEi, gross energy intake.
A00, A15, A30, A45, A60, and A75: peanut haulm incorporation levels at 0%, 15%, 30%, 45%, 60%, and 75%, respectively. N00, N15, N30, N45, N60, and N75: cowpea haulms incorporated at 0%, 15%, 30%, 45%, 60%, and 75%, respectively. Values with the same letter in each column do not differ significantly at the 5% level.

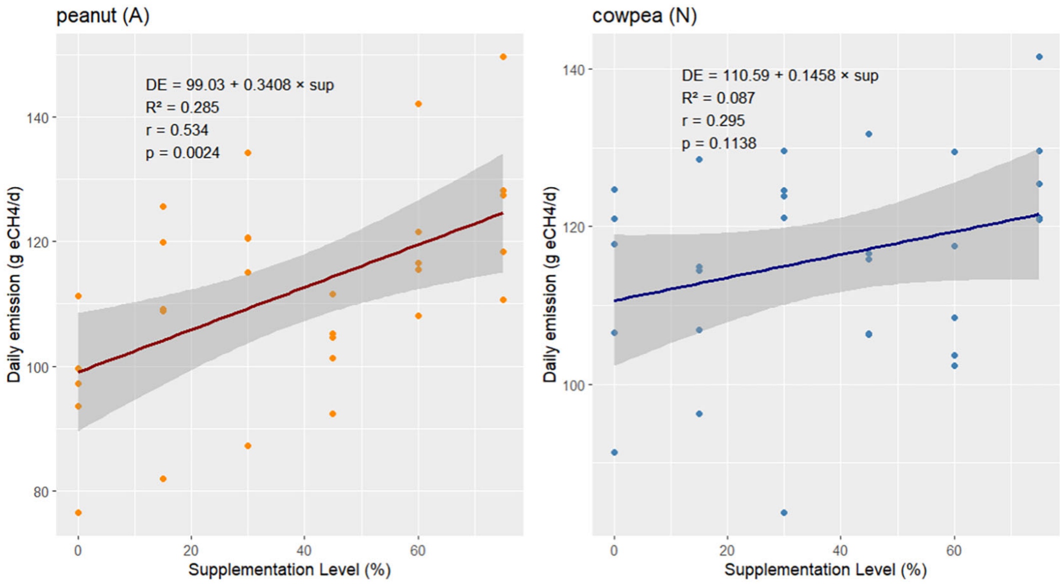

FIGURE 6
Regression lines for daily emissions by incorporation levels of peanut (A) and cowpea (N) haulms.

BW), a period characterized by low forage quality and limited availability. However, they remain below the intake levels recorded during the cool dry season (22.3 g/kg BW), when forage quality is relatively higher and crop residues are still accessible in the fields.

Dry matter intake (DMi), expressed both in kg/day and g/kg BW, increased steadily with rising levels of legume haulm supplementation. At inclusion rates of 60% and 75%, intake exceeded the benchmark value of 25 g DM/kg BW, commonly attributed to grazing cattle in Sub-Saharan Africa (Rivière, 1991), which is considered an overestimate, as well as the 18 g DM/kg BW/day standard proposed by Assouma et al. (2018) for the average annual intake of grazing cattle in semiarid environments.

In terms of ingested feed composition, CP contents increased linearly with supplementation, while fiber fractions (CF, NDF, and ADF) declined. These trends align with the findings by Assoumaya et al. (2007), who reported that increasing CP content from 5% and 10% enhances both intake and digestibility. In the present study, CP content rose from 4.5% to over 10% of DMi at higher supplementation levels (60%–75%), corresponding with intake increases ranging from 12% to 48%.

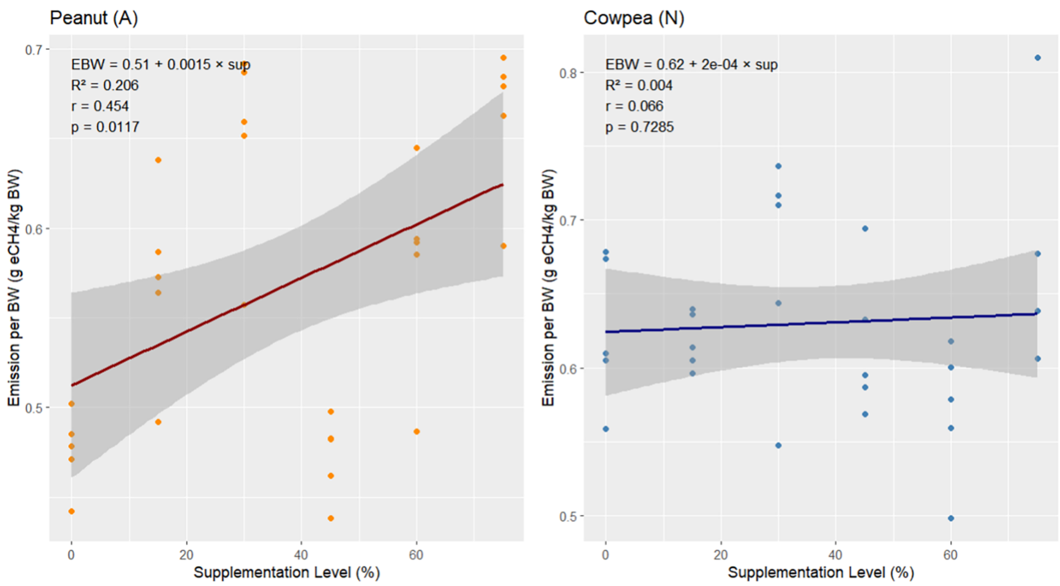

FIGURE 7
Regression lines for emissions per body weight by incorporation levels of peanut (A) and cowpea (N) haulms.

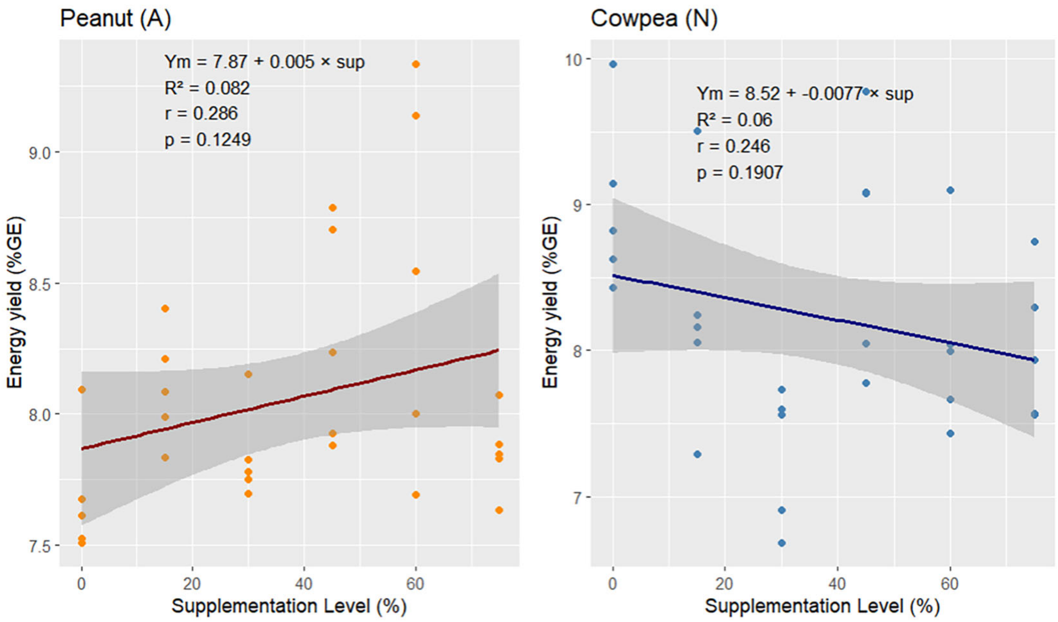

FIGURE 8
Energy yield regression lines by incorporation levels of peanut (A) and cowpea (N) haulms.

Neutral detergent fiber (NDF), the primary component of plant cell walls, plays a critical role in regulating intake due to its impact on rumen fill and digestive tract congestion (Archimède et al., 2011; Oba and Kammes-Main, 2023). Rations with high NDF content (>60% DM), notably the control and low-supplemented rations (15%–30%), were associated with lower intake levels. These fibrous feeds are bulkier and less palatable, limiting voluntary consumption. In contrast, rations with higher legume haulm inclusion were less fibrous, more palatable, and easier to ingest, consistent with the observations by Barbosa et al. (2018). To accommodate the increased palatability and intake potential of these supplemented rations, the feed offer was raised from 2.5% to 3% of animal BW at 60% and 75% inclusion levels, ensuring a minimum refusal rate of 10%. Despite this adjustment, these diets yielded the lowest refusal rates observed in this study, further confirming their superior acceptability and intake efficiency.

Across all rations, the CP content of ingested feed was consistently higher than that of the offered feed, while ingested fiber content was lower. This discrepancy is attributed to the animal's selective feeding behavior, whereby cattle voluntarily sort and consume the more palatable component of the ration, typically legume haulms or the leafy tops of grasses, while rejecting coarser, more fibrous, and lignified parts such as stalks. Through this selection process, animals effectively construct a nutritionally richer diet than what is initially offered (Archimède et al., 2011). Interestingly, at the highest supplementation level (75%), this trend reversed: animals tended to prioritize grass hay over legume haulms, likely in an effort to balance their intake and avoid excessive protein or reduced fiber, suggesting a form of nutritional self-regulation. GEi increased significantly with supplementation, rising from 18.3 MJ/kg DM under the control ration to over 18.6 MJ/kg DM at 60% legume haulm inclusion. This improvement reflects both the enhanced quality of the supplemented fodder and the greater quantity consumed. These findings are consistent with those of Gbenou et al. (2024c), who reported that legume coproducts generally possess higher protein and energy densities than grasses and contribute to improved feed intake when used as supplements in ruminant diets.

4.3 Apparent digestibility coefficients

Unlike fiber digestibility, the apparent digestibility of DM, OM, and CP was relatively low for the control ration. Notably, apparent digestibility for the control diet varied between the two animal batches. Batch 1, previously exposed to peanut haulm supplementation, exhibited digestibility coefficients more than 3.5 percentage points higher than batch 2, which had received cowpea haulms. This discrepancy was consistent across all measured parameters, DM, OM, CP, NDF, and ADF, and is attributed to residual effects from earlier supplementation phases. The control ration was administered at the end of the trial period, following legume-supplemented feeding phases, suggesting that prior exposure to different legume types may have influenced microbial adaptation and digestive efficiency. The average DMd for the control ration (50.3%) aligns closely with the values reported for *Panicum* straw (50%) by Sana (2015) and with the digestibility of rangeland fodder during the cool dry season (50.5%) as documented by Gbenou et al. (2024b). These figures underscore the limited digestibility of mature tropical grasses when used as sole feed sources.

Supplementation with legume haulms significantly improved apparent digestibility parameters. DMd values ranged from 52% to

55%, exceeding typical values for dry-season rangeland fodder and grass straw (Gbenou et al., 2024b; Millogo et al., 2019) and approaching those recorded during the wet season (57.21%), when animals consume fresh, diverse, and highly digestible herbaceous vegetation (Gbenou et al., 2024b). These findings are consistent with Sana (2015), who reported that supplementing *Panicum* hay with 40% cowpea haulms increased DMd from 48% to 56% and OMd from 49% to 58%, reinforcing the value of legume haulms in enhancing the nutritional quality of low-grade tropical forages.

CPd is generally influenced by two opposing factors: the negative impact of cell wall content and the positive effect of the dietary CP content (Archimède et al., 2011). The observed increase in CPd with legume haulm supplementation reflects improved protein availability and reduced fiber density. Interestingly, while Gbenou et al. (2024c) used similar feed resources, their study reported lower CPd values for supplemented rations compared to the control, contrasting with the present findings. Here, CPd values for the control ration were particularly low (18.9% and 2.9% for the two animal batches), highlighting the limited protein utilization from *Panicum* hay alone.

The timing of control ration administration, at the end of the trial, coincided with the signs of weight loss in animals, likely due to the reduced nutritional quality of the diet. This decline in body condition suggests mobilization of internal reserves, particularly muscle tissue, to meet basal energy requirements (Guarnido-Lopez, 2022). In contrast, animals fed supplemented rations generally gained weight, reflecting improved nutrient intake and utilization.

In rations with low crude protein content (e.g., 4.1% DM), CP digestibility (CPd) is not a reliable indicator of protein utilization, because the high proportion of endogenous nitrogen in feces is relatively high. Ruminants can recycle substantial amounts of urea in the rumen, converting it into microbial protein, an adaptive mechanism that compensates for dietary protein deficiencies (Archimède et al., 2011; Guarnido-Lopez, 2022; INRA, 2018). Consequently, total protein flow to the intestine may exceed the amount of protein ingested.

Fiber digestibility parameters (CFd, NDFd, ADFd) and intake were inversely related to CPd, OMd, and DMd, consistent with the findings of Barbosa et al. (2018). This inverse relationship reflects the trade-off between structural carbohydrate content and nutrient availability: as fiber concentration increases, digestibility and intake of more digestible components tend to decline.

Linear regressions and extrapolations that were conducted based on apparent digestibility values obtained from supplementation levels of 15%, 30%, 45%, 60%, and 75%. While feeding ruminants a 100% legume haulm diet is not advisable due to risks such as acidosis, toxicity, and diarrhea (INRA, 2018; Sauvant and Giger-Reverdy, 2015), regression analysis remains valuable for illustrating digestibility trends. In this study, linear regression models were significant for most digestibility parameters, validating extrapolation to 100% haulm inclusion.

Apparent digestibility of DM, OM, CF, NDF, and ADF followed linear trends with increasing supplementation. However, CP digestibility (CPd) did not exhibit a linear relationship, and acid detergent lignin digestibility (ADLd) showed no significant regression ($p > 0.05$) and a low coefficient of determination ($R^2 = 0.22$), rendering extrapolation unreliable for these two components.

CPd followed a second-degree polynomial trend, likely reflecting protein underfeeding bias at lower supplementation levels (0% to 30%), where CP content remained below the critical threshold of 7% DM. Below this threshold, rumen microbial activity is impaired, limiting fermentation and nutrient utilization (Miliford and Minson, 1965). Forages with CP content below 7% are considered protein-deficient for ruminant nutrition (Archimède et al., 2019). By contrast, the CP content of legume haulms used in this study exceeded the 7% DM threshold, supporting effective microbial function and improved protein digestibility.

Finally, the experimental design, based on successive diet distribution, may have introduced microbial adaptation effects and altered nutritional status, potentially influencing ruminal ecosystem dynamics and digestibility outcomes (Malmuthuge and Guan, 2017). However, this effect is likely minimal, as all diets contained the same ingredients and adaptation periods were implemented to stabilize ruminal metabolism between the two trials.

4.4 Enteric methane emissions

Daily eCH_4 production per animal averaged 95.6 g in batch 1 and 103 g in batch 2, respectively, a difference primarily attributed to the higher average body weight of animals in batch 2. The "animal" effect in ANOVA models was statistically significant for most variables, indicating that individual animals exhibited markedly different eCH_4 production levels regardless of diet (Wallace et al., 2015). Although the experimental design did not specifically target individual variability, the magnitude of these differences suggests the need for dedicated studies exploring genetic and microbiota-related factors influencing methane emissions (Malmuthuge and Guan, 2017; Zened et al., 2021).

Across both groups, eCH_4 emissions increased with legume haulm supplementation, driven by the corresponding rise in DMi. As animals consume more coarse fodder, fermentation activity in the rumen intensifies, leading to elevated methane production (Beauchemin et al., 2020; Soder and Brito, 2023). Supplementation also resulted in higher eCH_4 emissions per unit of body weight (g/kg BW), reflecting the metabolic inefficiencies associated with low-quality tropical forages at suboptimal intake levels. These inefficiencies amplify both absolute eCH_4 production (Doreau et al., 2017) and the methane conversion factor (Ym) of the ingested feed (Goopy et al., 2020). Despite the increase in absolute eCH_4 emissions, eCH_4 yield (g/kg DMI) declined with supplementation, indicating improved feed conversion efficiency. This trade-off, where productivity-enhancing strategies may raise total emissions but reduce emission intensity per unit of output, is central to climate-smart livestock production. In this study, eCH_4 yield decreased by 4%–6% with legume haulm inclusion, coinciding with improved digestibility parameters (DMd, OMd, CPd).

Lower eCH_4 emissions are typically associated with reduced cell wall content, faster rumen passage rates, and enhanced protein degradability (Baumont et al., 2016). The eCH_4 yield values recorded here align closely with the seasonal average value of 25.2 g/kg DMi reported by Gbenou et al. (2024b) during the cool dry season. Notably, legume haulms are commonly used during the hot dry season, when forage availability and quality are critically low. Even so, the yields observed in this study were consistently lower than the 31.8 g/kg DMi reported by Gbenou et al. (2024c) for low-quality fodder supplemented with 25% haulms during the hot dry season. All recorded yields exceeded the IPCC, (2019) default annual average of 23.3 g/kg DMi for livestock in Sub-Saharan Africa, underscoring the importance of context-specific measurements.

eCH_4 emissions represent a significant loss of GEi, ranging from 2% to 12%, depending on diet and animal physiology (Johnson and Johnson, 1995; Popova et al., 2011). In this study, the calculated Ym was approximately 8.1% of GEi, consistent with the values reported during the cool dry season (Gbenou et al., 2024b) and comparable to the findings from tropical cattle fed crop residues in Thailand (Kaewpila and Sommart, 2016). In contrast, selectively bred African cattle for dairy or meat production exhibit lower Ym values, averaging approximately 3.8% GEi (Noguera and Posada-Ochoa, 2017), highlighting the influence of genetic potential and feed quality on methane-related energy inefficiencies.

It is also plausible that rumen adaptation influenced the observed eCH_4 responses. Prior exposure to mixed diets may have shaped the rumen microbiota, facilitating partial adaptation to haulm-based rations and affecting fermentation efficiency and hydrogen utilization.

5 Conclusion

Under typical agropastoral conditions in Africa, forage quality is often poor, particularly during the dry season. This study showed that supplementing cattle diets with legume haulms, especially peanut (75%) and cowpea (45%), enhanced nutritional value and significantly reduced eCH_4 emissions. These results underscore the potential of legume haulms as a sustainable feed strategy for mitigating greenhouse gas emissions in tropical livestock systems. However, the limited number of animals constrained the ability to test all rations simultaneously. While the study was conducted under controlled station conditions suitable for intensive metabolism trials, this may limit the direct applicability of the findings to field settings. Long-term success will depend on factors such as haulm availability and integration into large-scale feeding systems. Further research should explore optimal harvesting and storage practices, evaluate other protein-rich legumes (including woody forages), and use iso-protein diets to distinguish legume-specific effects. Integrating emission intensity metrics linked to productivity (e.g., milk and meat yield) would likely provide a more comprehensive view of environmental and performance trade-offs, guiding sustainable livestock management in tropical regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by the CIRDES Ethics Committee for Animal Experiments under application number 006/Mars/2021/CE CIRDES, dated 15 April 2021. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

BDS: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Investigation, Software. DB: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing, Supervision. GG: Conceptualization, Data curation, Methodology, Validation, Writing – review & editing. WH: Investigation, Methodology, Writing – review & editing. OS: Investigation, Supervision, Validation, Writing – review & editing. LD: Conceptualization, Data curation, Supervision, Validation, Writing – review & editing. LB: Data curation, Formal analysis, Software, Writing – review & editing. MB: Supervision, Validation, Writing – review & editing. HA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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