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Evaluation of Methane Emissions from Major Dairy Cattle Feed Resources and Identification of Low Methane-Emitting Feeds with Optimum Nutritional Quality in Central Ethiopia

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Abstract

This paper assesses the potential of major feed resources to mitigate methane (CH_4) emissions while improving animal productivity in Ethiopia. The objective was to evaluate methane emissions from major dairy cattle feed resources and identify low methane-emitting feeds with the required nutritional quality in central Ethiopia. In this study, twelve common dairy cattle feed resources were evaluated in terms of chemical composition, nutritive value, in vitro gas production, CH_4 production, and CH_4 concentration (%). The data were fitted to an exponential equation commonly used in comparable in vitro gas production studies. The effects of feed samples on nutritional composition and in vitro gas production were determined using a two-way ANOVA of R software version 4.2.3. The major feed resources differed significantly ($p < 0.05$) in chemical compositions, nutritive values, in vitro gas production, methane emission potential, and concentration. The current study found that all crop residues and natural pastures (roughages) had a crude protein (CP) concentration greater than 3.4± 0.11, whereas supplementary feed had more than 16.3±0.48 of DM. Natural pasture (7.1± 1.11) and bean straw (6.8± 0.11) had the highest CP level ($p < 0.05$), while wheat (3.4± 0.11), barley (3.8± 0.11), and teff straws (4.5 ± 0.11) had the lowest ($p < 0.05$). Similarly, noug seed cake (24.3± 0.48) and linseed cake (29.6± 0.48) had the highest CP level ($p < 0.05$), while compound feed (17.1± 0.48) and wheat bran (16.3± 0.48) had the lowest ($p < 0.05$) among supplementary feeds. The highest ($p < 0.05$) in vitro organic matter digestibility (IVOMD) and metabolizable energy (ME) were observed for natural pasture and wheat bran, while the lowest ($p < 0.05$) was for wheat straw and atela among roughages and supplementary feeds, respectively. Overall, the means of each chemical composition and the nutritive value of the selected major feeds were found within the ranges of previously reported values for Sub-Saharan African feeds. Hay produced the highest CH_4 (51.89 mL/0.2 g DM incubated) among roughages, while bean straw produced the lowest (40.25 mL/0.2 g DM). Among supplementary feeds, wheat bran produced the highest CH_4 (47.00 mL/0.2 g DM incubated), while atela produced the lowest (39 mL/0.2 g DM). Natural pasture had the lowest percentage of methane (19.33%), followed by barley straw (20.49%) and oat straw (26.23%). Similarly, wheat bran had the lowest methane concentration (4.64%), followed by compound feed (6.63%), compared to other types of supplementary feeds. Hay and wheat bran had the highest gas volume among roughages and supplementary feeds ($p < 0.05$) throughout the incubation periods. From the study, it was concluded that the identified supplementary feeds had high CP levels, suggesting that they can be used as high-protein and energy sources to supplement low-quality roughages. Therefore, wheat bran has the lowest methane concentration, the highest ME and IVOMD levels, and the fastest rate of fermentation (c), making it a reasonable supplement to low-quality roughages. Conversely, wheat straw exhibited the highest methane concentration, which can be effectively managed through chemical pre-treatment to improve nutritional qualities and reduce harmful methane emissions.

1. Introduction

Ethiopia's livestock population is estimated to be 66 million cattle, 38 million sheep, and 46 million goats, which are raised in a variety of production systems ranging from pastoral to mixed crop-livestock systems with various intensification degrees (CSA, 2021/22). Despite having a huge cattle population, the country's productivity is low, primarily due to poor nutrition (FAO, 2019; Mengistu et al., 2021). Correspondingly, dairy cattle production is crucial for smallholder farming in Ethiopia's central highlands; however, low milk productivity is primarily due to nutritional constraints (Ashagrie et al., 2023). This low productivity leads to high absolute CH_4 emissions, as well as high emissions per unit of product (Herrero et al., 2013). These emissions have a global significance, particularly in countries like Ethiopia, where substantial populations of ruminants live in mixed farming systems.

Greenhouse gas (GHG) emission rates might increase in the future due to population growth and changing diets (Thornton and Herrero, 2010; FDRE, 2021). These emissions significantly impact climate change, posing an ongoing threat to global food security. Feeding a growing population, ensuring rural households' livelihoods, lowering GHG emissions, and achieving the sustainable development goals are all required to reduce agricultural GHG emissions by 4% and lift 137 million people out of hunger by 2030 (Nenert et al., 2025). The agricultural industry is considered both a contributor to greenhouse gas (GHG) emissions and a possible source of solutions. As global food demand increases, the challenge is to mitigate the environmental impact of agricultural production while maintaining food security (OECD/FAO, 2025).

Shortage and poor feed quality are major barriers to increasing dairy cattle productivity in underdeveloped countries. To meet the expected high demand for dairy and related products and achieve future goals of feeding millions while ensuring food security, it is essential to utilize better feed resources that do not compete with human food and minimize environmental harm. Moreover, there is a need to identify major feed sources and low-methane-emitting, highly nutritious feed options, as well as to address the significant gap between supply and demand for animal feed. There is also inadequate information for mapping the nutritional status of dairy cattle in central Ethiopia and for designing necessary development plans. A knowledge-based improvement in the nutritional management of dairy cattle is essential for maintaining the sustainability of dairy farming in Ethiopia. This is particularly important considering Ethiopia's current focus on sustainable feed resource utilization, which aims to maximize dairy cattle productivity while reducing greenhouse gas emissions, especially CH_4. In addition, feed resources identification and nutritional quality are the most important factors influencing dairy cattle productivity. The quantity and quality of feed resources are subject to frequent fluctuations due to a number of variables, making the most recent data essential (Feyisa et al., 2021).

Evaluating the nutritional value of feed is crucial because it influences the protein and energy intake of animals (Cline et al., 2010). Usually, the nutrient content of feed ingested by animals has been assessed using *in vitro* organic matter digestibility or in situ organic matter degradability (Waterman et al., 2007). However, studies with live animals (in vivo) are time-consuming, expensive, labor-intensive, and require large quantities of feed (France et al., 2005). Gas production was one of the most used ways for assessing *in vitro* feed quality. The *in vitro* gas production techniques were developed by Menke and Steingass (1988) to evaluate the nutritional value of feeds and to indirectly quantify the rate and amount of DM degradation by using the gas produced during fermentation. The determination of *in vitro* gas production parameters is critical because it gives information on the fermentation kinetics of feeds consumed by ruminants, which are dependent on the rate of passage and degradation (Mould et al., 2005). The kinetic parameters of degradation are critical for a better understanding of rumen fermentation since they describe digestion as well as the intrinsic features of substrates (Wang et al., 2025).

According to Jancík *et al*. (2010), ruminant nutrient use is highly influenced by the rate and extent of DM fermentation in the rumen. *In vitro* gas production has been commonly utilized to assess the nutritional content of feed resources (Murillo et al., 2012) as well as in improved feeds (Valizadeh *et al*., 2008). However, there is limited information on the nutritional qualities and content of the major feed sources for dairy cattle in central Ethiopia, as well as insufficient data on CH_4 emissions from these sources. Hence, understanding the existing major feed resources, their chemical composition, nutritional values, and methane emissions is important for identifying low-methane-emitting feeds with the necessary nutritional quality and designing appropriate interventions to improve feed supply, thereby increasing dairy cattle productivity and reducing methane emissions. It is hypothesized that the major feed resources in central Ethiopia exhibit significant seasonal variation in their chemical composition, nutritive values, and CH_4-emission potentials, and that these variations may be used to enhance the feed resources and promote environmental sustainability. Therefore, the objective of this study was to evaluate the nutrient composition, *in vitro* gas and methane production from major dairy cattle feed resources, and identify low-methane-emitting feeds with the required nutritional quality in central Ethiopia.

2. Materials and Methods

2.1. Feed sample collection and preparation

Representative samples of all major feed resources used by dairy cattle in the study areas were obtained from various households and their grazing sites. The major feed sources are the feeds that are regularly used for dairy cattle in the community. The feed types were selected based on information gathered from household interviews and focus group discussions. Accordingly, twelve different feed samples, namely wheat straw, barley straw, teff straw, bean straw, oat straw, natural pasture hay (hay), wheat bran, compound feed, linseed cake, Noug seed cake, brewery wet grain (Atela), and natural pasture grazing (natural pasture) were selected from major dairy cattle feed resources based on their significance and value to the animals. To generate representative samples, the collected samples were pooled for each feed type. Samples were collected from each household based on its kind and similarity. Feed samples were properly labeled in the field to ensure full information.

A representative natural pasture grazing feed sample was collected immediately before the grazing period to accurately characterize the feeds available to the animals (Rayburn, 2014). Sampling was done by walking systematically throughout the field in a "M" or grid pattern (every 20–50 steps) to cover the area uniformly and avoid bias (Goosey, 2022). At each sampling point, small grab samples were collected by sickle or cutting feed at a height comparable to the livestock's grazing height to capture the part of the pasture that the animals would consume (Rayburn, 2014).

The collected subsamples were placed in a clean bucket or container. Once a sufficient amount of material had been collected, the contents of the container were thoroughly combined to make the composite sample. If the composite sample was too large, the quartering process was used to reduce it to about one quart for easier handling and transport. The final composite sample was placed in a labeled sample bag with the pasture name and collection date. During the wet season, samples were green and had a high moisture content; so, they were air-dried to minimize mold growth during transit, which could affect nutritional quality. Air drying was accomplished by spreading the sample evenly on a clean surface in a warm, shady place for a few days, avoiding direct sunshine, until the sample was air-dry. Samples were then transported early in the week to Hawassa University's Animal and Range Sciences school nutrition laboratory.

Samples of representative feed were subsampled, partially dried in an oven at 60°C for 48 hours, followed by grinding through a 1-millimeter sieve or mesh screen, sealed in a clean, airtight plastic bag, and kept until the analysis was done for chemical composition and *in vitro* gas production. The collected, sub-sampled, and ground feed samples were then used to perform *in vitro* gas production and determine essential nutritional components (dry matter, crude protein, ash, neutral detergent fiber, acid detergent fiber, acid detergent lignin, metabolizable energy, and *in vitro* dry matter digestibility).

2.2. Chemical analysis of major feed resources

The chemical composition and *in vitro* CH_4 gas production of samples from the major feed resources were identified and analyzed at the nutrition laboratory of the School of Animal and Range Sciences, Hawassa University, Ethiopia. The feed samples were evaluated for their Dry matter (DM), Ash, and Crude protein (CP), and Ether extract (EE) contents were analyzed by the standard methods of AOAC (2005). The ether extract (EE) content of a sample was determined using the Soxhlet extraction method, and the nitrogen content of feed samples was evaluated using the Kjeldahl method. Crude protein (CP) was calculated as N × 6.25 (AOAC, 2005). Neutral detergent fiber (NDF), Acid detergent fiber (ADF), and Acid detergent lignin (ADL) were determined based on the method of Van Soest et al. (1991) using an Ankom 220 fiber analyzer (Ankom Technology®, Macedon, NY, USA). NDF was determined without alpha amylase. For ADL estimation, residue from the ADF determination was treated with 72 percent sulfuric acid. Eventually, the chemical analysis was performed twice.

The ME value shows the energy available from the feed for metabolism after losses in feces, urine, and gases, which is essential in determining feed quality for animals. The *in vitro* metabolizable energy (ME, MJ kg-1 DM) and organic matter digestibility (OMD) contents of the samples were determined using Menke and Steingass' (1988) equations based on ash, CP contents, and net gas production (GP) (corrected for blank) after 24 hours of incubation (ml per 200mg DM);

$$\mathrm{ME}\ (\mathrm{MJ/kg\,DM}) = 2.20 + 0.136{*}\mathrm{G_P} + 0.057{*}\mathrm{CP}$$

$$\mathrm{IVOMD}\ (\%) = 14.88 + 0.889{*}\mathrm{G_P} + 0.45{*}\mathrm{CP} + 0.0651{*}\mathrm{Ash}$$

Where, GP = Gas production over 24 hours of incubation, which is expressed in mL per 200 mg DM, CP = Crude protein content of feed samples, and ash (% DM).

2.3. *In vitro* gas and methane production

The major livestock feed resources collected were used for *in vitro* gas and methane production. The *in vitro* gas and methane productions were measured using the method developed by Menke and Steingass (1988). Rumen fluid was obtained from an animal slaughterhouse. Ruminal fluid was collected in the morning into a pre-warmed thermos flask (39 ^{0}C) that had previously been filled with CO_2 to maintain anaerobic conditions. The pooled ruminal fluid was strained through 8 layers of gauze, flushed with CO_2 (Mabjeesh et al., 2000), and mixed with Menke's buffer (incubation medium) at a 1:2 ratio (v/v). The rumen fluid was moved to a sizable glass beaker within a water bath set at 39°C, where it was constantly stirred and purged with CO_2. The inoculum (rumen fluid + buffer) was prepared using the method described by Menke and Steingass (1988).

2.3.1. Incubation to determine gas production and methane

In two different runs/replications, approximately 200 mg DM of the feed sample was incubated in triplicate in 100 mL preheated syringes. In both runs, each sample was tested three times (with three syringes), and two blank syringes containing the culture media solution and rumen fluids were incubated. Syringes carrying feed samples were pre-warmed at 39 ^{0}C, and their pistons were greased with Vaseline to assist movement and prevent gas from escaping before being inoculated with 30 mL of inoculum (10 mL rumen + 20 mL buffer mixture) while being flushed with continuous CO_2. The buffer solution (Onodera & Henderson, 1980) with rumen fluid (at a ratio of 1:2) was poured into the preheated syringe and incubated in a water bath at 39^{0}C. Syringes were shaken manually every hour for the first 8 hours (including 0 hours) of incubation (Abdulrazak et al., 2000), and then at each recording time (Chenost et al., 2001).

Gas production was recorded before incubation (0 hours) and after 3, 6, 9, 12, 24, 48, 72, and 96 hours of incubation. There was a 96-hour incubation period. The total gas values were corrected for blank incubation. However, due to the absence of reference standards with established gas values in Ethiopia, no correction was made for the standard feed sample. The kinetics of methane gas production data were adjusted by fitting the mean gas volumes to the exponential equation as follows (Blummel and Ørskov, 1993):

$G = a + b\ (1\text{-}e^{-ct})$,

Where:

G = The volume of gas produced (ml/200mg OM) at time t,

a = The gas production from the immediately soluble fraction (ml),

b = The gas production from the insoluble but degradable fraction (ml)

a + b = is the potential gas production (ml) and

c = the rate constant of gas production (fraction/hour)

2.3.2. Determination of total gas production, CH_4 gas production, and CH_4 gas concentration

Total gas production was determined by reading the piston position at each time point. Net gas production was estimated by subtracting the mean blank values from the volume of gas produced by incubated feeding. Gas production (ml/200 mg) at t hours was determined using the formula provided by Amsalu et al. (2018):

$$Gt = \frac{[(Vt - Vo - Go) * 200}{Ws}$$

Where;

Gt = gas production value (ml/200 mg) at t hours,

Vt = volume in ml at t hours,

V0 = volume in ml at the beginning,

G0 = the average gas production of blank syringes (ml), and

Ws = weight of dried sample in mg.

Methane production was measured after incubation using the procedure given by Fievez et al. (2005). In order to prevent gas escape, a connector (silicon tube) was inserted between a syringe containing NaOH solution and the incubation syringe to introduce 4 mL of NaOH (10 M) into the incubated contents in each syringe. The incubation syringes were shaken, and the leftover gas volume was measured. Mixing the incubated contents with NaOH allowed CO_2 to be absorbed, while the gas volume remaining in the syringe was considered as CH_4 (Demeyer *et al*., 1988, cited in Fievez et al., 2005). Test experiments reveal that CH_4 volumes measured after CO_2 absorption from *in vitro* incubations in syringes are compatible with values obtained using gas chromatography, as

demonstrated for numerous feedstuffs (Fievez et al. 2005). Net methane gas productions were calculated by the difference between methane and total gas in the test syringe and the corresponding blank. The CH_4 concentration (percentage) was determined (Jayanegara et al., 2009) as:

$$\text{Methane concentration } (\%) = \frac{\text{Net methane production}}{\text{Net total gas production}} * 100$$

Where:

Net methane production is the volume of methane produced, and

Net total gas production is the total volume of gas produced during the incubation period.

2.4. Data Analysis

A two-way ANOVA was used to determine the effects of feed samples on chemical composition, nutritive values, methane production, and concentration. Treatments were the major feed sources. Gas production data from triplicate syringes for each sample per incubation run were averaged before statistical analysis. Data on *in vitro* gas production and kinetics parameters were analyzed using factorial ANOVA arrangement with the feed sample as the treatment component (fixed effects), the incubation run (0, 3, 6, 9, 12, 24, 48, 72, and 96 hours as a blocking factor, and season (random effects) in a completely randomized design based on the following model:

$Y_{ijkl} = \mu + \alpha_i + \beta_j + \delta_k + \alpha\beta_{ij} + \alpha\beta\delta_{ijk} + \varepsilon_{ijkl}$;

Where:

Y_{ijkl} = is the response variable;

μ = overall mean;

α_i = Feeds effect;

β_j = effect of the Incubation;

δ_k = effect of the season (Dry or Wet);

$\alpha\beta_{ij}$ = Effect of the feed × Incubation interaction;

$\alpha\beta\delta_{ijk}$ = Effect of feed × season ×incubation interaction;

ε_{ijkl} = the random residual error.

Chemical composition, nutritive values, methane production, and concentration data were analyzed in a completely randomized design based on the following model:

$\mathbf{Y_{ijk} = \mu + F_i + S_j + (FxS)_{ij} + e_{ijk}}$

Where

Y_{ijk} =is the response variable;

μ = is the overall mean;

F_i = the fixed treatment effect (i^{th} feed sample);

S_j = effect of season (random) and

FxS_{ij} = the interaction effect between the i^{th} feed sample and the j^{th} season

e_{ij} = the residual error term or the random experimental error

Curve fitting techniques were used to quantitatively analyze the cumulative gas production data from the anaerobic incubation of feed with rumen fluid in order to characterize the fermentation kinetics and estimate pertinent parameters. A correlation analysis was conducted to quantify the relationship between methane production and concentration, *in vitro* gas production parameters, and chemical composition and nutritive values by using R software version 4.2.3. Results were given as least-squares means with standard errors. The least significant difference (LSD) test was used to compare means that were significantly different ($p < 0.05$).

3. Results

3.1. Chemical Composition and Nutritive Values of Crop Residues and Natural Pastures

The chemical composition and nutritive values of the major feed resources under study differed significantly ($p < 0.05$) among feed types (Table 1). The mean DM content of all roughages (crop residues and natural pastures) selected for this study fell between 89.6± 0.49 and 92.3± 0.49. There was a significant difference ($p < 0.05$) in the DM contents among crop residues and natural pastures. However, no significant difference ($p > 0.05$) was found among bean straw, oat straw, wheat straw, hay, and natural pasture. Bean straw and natural pasture had the lowest ($p < 0.05$) ash content, while wheat straw had the highest ($p < 0.05$).

All crop residues and natural pastures identified in the study had a CP content ranging from 3.4±0.11 to 7.1± 1.11 of DM. Barley, wheat, and oat straw had the lowest ($p < 0.05$) EE content, whereas natural pasture and hay had the highest ($p < 0.05$). The crop residues and natural pastures had NDF and ADF values ranging from 44.9±0.52 to 72.0±0.52 and 38.9±0.74 to 46.6±0.74 of DM, respectively. Teff, wheat, and barley straw had the highest ($p < 0.05$) NDF concentrations, while bean had the lowest ($p < 0.05$). The identified crop residues and natural pastures had IVOMD and ME levels ranging from 42.8 ± 0.44 to 56.2± 0.44 and 6.3 ± 0.07 to 8.4 ± 0.07 of DM, respectively.

Table 1
Chemical composition and nutritive values of crop residues and natural pastures (Mean±SEM)

Chemical Composition	Barley straw	Bean straw	Hay	Natural pasture	Oat straw	Teff straw	Wheat straw
DM	89.6± 0.49^{c}	92.3± 0.49^{a}	91.6± 0.49^{ab}	92.0± 0.49^{ab}	91.7±0.49^{ab}	91.2± 0.49^{b}	91.4±0.49^{ab}
Ash	8.0± 0.16^{b}	5.8± 0.16^{d}	7.2± 0.16^{c}	6.0± 0.16^{d}	7.9±0.16^{b}	6.8± 0.16^{c}	8.6±0.16^{a}
CP	3.8± 0.11^{e}	6.8± 0.11^{b}	5.5± 0.11^{c}	7.1± 0.11^{a}	5.3±0.11^{c}	4.5± 0.11^{d}	3.4±0.11^{f}
EE	1.5± 0.03^{d}	1.9± 0.03^{c}	2.0± 0.03^{b}	2.1± 0.03^{a}	1.6±0.03^{d}	1.9± 0.03^{c}	1.6±0.03^{d}
NDF	71.3± 0.52^{a}	44.9± 0.52^{d}	62.8± 0.52^{c}	70.0± 0.52^{b}	69.0±0.52^{b}	72.0±0.52^{a}	71.3±0.52^{a}
ADF	45.3±0.74^{a}	43.1± 0.74^{b}	38.9± 0.74^{d}	46.6± 0.74^{a}	45.1±0.74^{a}	41.5± 0.74^{c}	43.3±0.74^{b}
ADL	5.8± 0.19^{c}	8.4± 0.19^{b}	4.2± 0.19^{e}	9.6± 0.19^{a}	5.0± 0.19^{d}	4.3± 0.19^{e}	5.1± 0.19^{d}
IVOMD	50.1± 0.44^{c}	55.8± 0.44^{a}	54.2± 0.44^{b}	56.2± 0.44^{a}	48.6± 0.44^{d}	46.6± 0.44^{e}	42.8± 0.44^{f}
ME	7.5± 0.07^{c}	7.8± 0.07^{b}	8.1± 0.07^{b}	8.4± 0.07^{a}	7.1± 0.07^{d}	6.9± 0.07^{e}	6.3± 0.07^{f}

The different superscript letters within the row indicate a significant difference ($p < 0.05$). DM = Dry matter, CP = Crude protein, EE = Ether Extract, NDF = Neutral detergent fiber, ADF = Acid detergent fiber, ADL = Acid detergent lignin, IVOMD = *In vitro* organic matter digestibility, ME = Metabolizable energy

There were significant differences ($p < 0.05$) in the chemical composition and nutritive values of the crop residues and natural pastures between the wet and dry seasons (Table 2). However, there was no significant seasonal difference ($p > 0.05$) in EE and NDF contents of bean straw, ash content of hay, and EE of oat straw between dry and wet seasons. Similarly, there was no significant difference ($p > 0.05$) in IVOMD and ME contents among feed samples from roughages, except for the ME content of natural pasture between dry and wet seasons.

Table 2
Seasonal chemical composition and nutritive values of roughages under the study (Mean ± SEM)

Chemical Composition	Seasons	Barley straw	Bean straw	Hay	Natural pasture	Oat straw	Teff straw	Wheat straw
DM	Dry	91.7± 0.70^{a}	93.0± 0.70^{a}	92.4± 0.70^{a}	93.7± 0.70^{a}	92.9± 0.70^{a}	92.0± 0.70^{a}	93.7± 0.70^{a}
	Wet	87.5± 0.70^{b}	91.6± 0.70^{b}	90.8± 0.70^{b}	90.3± 0.70^{b}	90.5± 0.70^{b}	90.4± 0.70^{b}	89.1± 0.70^{b}
Ash	Dry	9.8± 0.23^{a}	6.1± 0.23^{a}	7.3± 0.23	5.1± 0.23^{b}	8.2± 0.23^{a}	8.4± 0.23^{a}	9.8± 0.23^{a}
	Wet	6.3± 0.23^{b}	5.6± 0.23^{b}	7.0± 0.23	6.8± 0.23^{a}	7.6± 0.23^{b}	5.3± 0.23^{b}	7.5± 0.23^{b}
CP	Dry	4.5± 0.16^{a}	7.7± 0.16^{a}	6.5± 0.16^{a}	4.6± 0.16^{b}	6.4± 0.16^{a}	5.0± 0.16^{a}	4.1± 0.16^{a}
	Wet	3.1± 0.16^{b}	5.9± 0.16^{b}	4.5± 0.16^{b}	9.7± 0.16^{a}	4.2± 0.16^{b}	4.0± 0.16^{b}	2.8± 0.16^{b}
EE	Dry	2.0± 0.04^{a}	1.9± 0.04	2.1± 0.04^{a}	1.4± 0.04^{b}	1.2± 0.04	2.1± 0.04^{a}	2.0± 0.04^{a}
	Wet	1.0± 0.04^{b}	1.8± 0.04	1.9± 0.04^{b}	2.8± 0.04^{a}	2.1± 0.04	1.8± 0.01^{b}	1.1± 0.04^{b}
NDF	Dry	68.5± 0.74^{b}	44.4± 0.74	58.1± 0.74^{b}	72.9± 0.74^{a}	63.6± 0.74^{b}	70.0± 0.74^{b}	66.4± 0.74^{b}
	Wet	74.2± 0.74^{a}	45.5± 0.74	67.5± 0.74^{a}	67.2± 0.74^{b}	74.4± 0.74^{a}	74.1± 0.74^{a}	76.1± 0.74^{a}
ADF	Dry	39.7± 1.04^{b}	40.9± 1.04^{b}	36.9± 1.04^{b}	51.1± 1.04^{a}	40.8± 1.04^{b}	35.7± 1.04^{b}	35.4± 1.04^{b}
	Wet	50.9± 1.04^{a}	45.2± 1.04^{a}	40.8± 1.04^{a}	42.1± 1.04^{b}	49.4± 1.04^{a}	47.2± 1.04^{a}	51.1± 1.04^{a}
ADL	Dry	3.8± 0.27^{b}	7.9± 0.27^{b}	2.8± 0.27^{b}	10.5± 0.27^{a}	4.2± 0.27^{b}	3.0± 0.27^{b}	3.6± 0.27^{b}
	Wet	7.8± 0.27^{a}	9.0± 0.27^{a}	5.6± 0.27^{a}	8.7± 0.27^{b}	5.9± 0.27^{a}	5.6± 0.27^{a}	6.7± 0.27^{a}
IVOMD	Dry	50.7± 0.62	56.3± 0.62	54.4± 0.62	55.6± 0.62	48.8± 0.62	47.3± 0.62	43.1± 0.62
	Wet	49.6± 0.62	55.3± 0.62	54.0± 0.62	56.8± 0.62	48.4± 0.62	46.0± 0.62	42.5± 0.62
ME	Dry	7.5± 0.09	7.9± 0.09	8.1± 0.09	8.2± 0.09^{b}	7.2± 0.09	7.0± 0.09	6.4± 0.09
	Wet	7.4± 0.09	7.7± 0.09	8.1± 0.09	8.5± 0.09^{a}	7.1± 0.09	6.8± 0.09	6.3± 0.09

The different superscript letters indicate there is a significant difference ($p < 0.05$) within the column. DM = Dry matter, CP = Crude protein, EE = Ether Extract, NDF = Neutral detergent fiber, ADF = Acid detergent fiber, ADL = Acid detergent lignin, IVOMD = *In vitro* organic matter digestibility, ME = Metabolizable energy

3.2. Chemical composition and Nutritive Values of supplementary feeds

Chemical compositions and nutritive values of supplementary feeds varied significantly ($p < 0.05$) among feed types (Table 3). However, there was no significant difference ($p > 0.05$) in CP content among atela and noug seed cake, and compound feed and wheat bran. Similarly, there was no significant difference ($p > 0.05$) in EE content among atela, compound feed, and wheat bran.

Table 3
Chemical composition and nutritive value of the supplementary feed resources under the study (Mean ± SEM)

Chemical Composition	Atela	Linseed cake	Noug seed cake	Compound feed	Wheat bran
DM	91.7± 0.36^{b}	93.0± 0.36^{a}	92.8± 0.36^{a}	90.9± 0.36^{c}	90.8±0.36^{c}
Ash	4.0± 0.05^{e}	6.8± 0.05^{c}	10.3± 0.05^{a}	9.6± 0.05^{b}	5.8±0.05^{d}
CP	24.3± 0.48^{b}	29.6± 0.48^{a}	24.3± 0.48^{b}	17.1± 0.48^{c}	16.3± 0.48^{c}
EE	3.6± 0.19^{c}	7.4± 0.19^{b}	9.2± 0.19^{a}	3.5± 0.19^{c}	3.8± 0.19^{c}
NDF	52.1± 0.70^{a}	27.6± 0.70^{d}	41.9± 0.70^{b}	35.3± 0.70^{c}	42.0± 0.70^{b}
ADF	20.6 ± 0.37^{c}	23.7±0.37^{b}	31.7±0.37^{a}	11.7±0.37^{e}	14.2±0.37^{d}
ADL	4.9± 0.04^{c}	7.5± 0.04^{b}	7.7± 0.04^{a}	3.8± 0.04^{d}	3.6± 0.04^{e}
IVOMD	47.1± 0.59^{d}	62.0± 0.59^{b}	56.5± 0.59^{c}	60.7± 0.59^{b}	69.4± 0.59^{a}
ME	6.8± 0.09^{d}	9.0± 0.09^{b}	8.2±0.09^{c}	8.9± 0.09^{b}	10.3± 0.09^{a}

Means in the same row with different superscripts differ significantly ($p < 0.05$). EE = Ether Extract, CP = crud protein, NDF = Neutral detergent fiber, ADF = Acid detergent fiber, ADL = Acid detergent lignin, IVOMD = *In vitro* organic matter digestibility, ME = Metabolizable energy

There was no significant difference ($p > 0.05$) in NDF content between noug seed cake and wheat bran. Atela exhibited the greatest NDF values (52.1±0.70), followed by noug seed cake (41.9±0.70) and wheat bran (42.0±0.70). Noug seed cake had the highest ($p < 0.05$) ADF concentration, while compound feed had the lowest ($p < 0.05$) concentration among the major supplementary feeds. Similarly, noug seed cake had the highest ($p < 0.05$) ADL concentration, and wheat bran had the lowest ($p < 0.05$) concentration among the supplementary feeds. IVOMD and ME concentrations in the supplementary feeds varied from 47.1 to 69.4% of DM and 6.8 to 10.3% of ME, respectively.

Seasonal variations in the chemical composition and nutritional values of supplementary feeds (protein and energy sources) are presented in Table 4, comparing the dry and wet seasons. The interaction of feeds and seasons was observed to have a significant ($p < 0.05$) effect on the majority of chemical compositions. However, there was no significant difference ($p > 0.05$) in NDF percentage of linseed cake and noug seed cake between the dry and wet seasons, and ADF contents of atela between both seasons. Similarly, there was no significant difference ($p > 0.05$) in IVOMD and ME of linseed cake, noug seed cake, and compound feed between the dry and wet seasons.

Table 4
Seasonal chemical composition and nutritive value of supplementary feed resources under the study (Mean ± SEM)

Chemical Composition	Seasons	Atela	Linseed cake	Noug seed cake	Compound feed	Wheat bran
DM	Dry	92.3± 0.51^{a}	93.2± 0.51^{a}	93.9± 0.51^{a}	93.0± 0.51^{a}	92.0± 0.51^{a}
	Wet	91.0± 0.51^{b}	91.9± 0.51^{b}	91.8± 0.51^{b}	88.8± 0.51^{b}	89.7± 0.51^{b}
Ash	Dry	2.5± 0.07^{b}	6.9± 0.07^{a}	11.7± 0.07^{a}	10.8± 0.07^{a}	6.0± 0.07^{a}
	Wet	5.6± 0.07^{a}	6.6± 0.07^{b}	8.9± 0.07^{b}	8.5± 0.07^{b}	5.7± 0.07^{b}
CP	Dry	28.3± 0.68^{a}	31.4± 0.68^{a}	27.0± 0.68^{a}	19.1± 0.68^{a}	16.7± 0.68
	Wet	20.3± 0.68^{b}	27.7± 0.68^{b}	21.7± 0.68^{b}	15.0± 0.68^{b}	15.9± 0.68
EE	Dry	5.0± 0.27^{a}	9.6± 0.27^{a}	10.9± 0.27^{a}	4.3± 0.27^{a}	4.4± 0.27^{a}
	Wet	2.1± 0.27^{b}	5.3± 0.27^{b}	7.4± 0.27^{b}	2.6± 0.27^{b}	3.3± 0.27^{b}
NDF	Dry	44.4± 0.99^{b}	27.0± 0.99	41.0± 0.99	31.9± 0.99^{b}	34.7± 0.99^{b}
	Wet	59.8± 0.99^{a}	28.1± 0.99	42.8± 0.99	38.7± 0.99^{a}	49.3± 0.99^{a}
ADF	Dry	20.5± 0.53	21.4± 0.53^{b}	30.5± 0.53^{b}	8.2± 0.53^{b}	13.1± 0.53^{b}
	Wet	20.7± 0.53	26.1± 0.53^{a}	32.8± 0.53^{a}	15.3± 0.53^{a}	15.3± 0.53^{a}
ADL	Dry	4.5± 0.06^{b}	6.4± 0.06^{b}	7.1± 0.06^{b}	2.8± 0.06^{b}	2.8± 0.06^{b}
	Wet	5.3± 0.06^{a}	8.6± 0.06^{a}	8.3± 0.06^{a}	4.8± 0.06^{a}	4.5± 0.06^{a}
IVOMD	Dry	48.5± 0.84^{a}	62.3± 0.84	57.0± 0.84	61.0± 0.84	71.1± 0.84^{a}
	Wet	45.8± 0.84^{b}	61.7± 0.84	56.1± 0.84	60.4± 0.84	67.8± 0.84^{b}
ME	Dry	7.1± 0.12^{a}	9.0± 0.12	8.2± 0.12	8.9± 0.12	10.5± 0.12^{a}
	Wet	6.6± 0.12^{b}	9.0± 0.12	8.2± 0.12	8.9± 0.12	10.0± 0.12^{b}

Means in the same column with different superscripts differ significantly ($p < 0.05$). EE = Ether Extract, CP = crud protein, NDF = Neutral detergent fiber, ADF = Acid detergent fiber, ADL = Acid detergent lignin, IVOMD = *In vitro* organic matter digestibility, ME = Metabolizable energy

Generally, the highest ($p < 0.05$) IVOMD and ME were observed for natural pasture and wheat bran, whereas the lowest ($p < 0.05$) were wheat straw and atela among roughages and supplemental feeds, respectively, in both seasons. Among roughages, natural pasture had the highest CP and wheat straw had the lowest ($p < 0.05$) in both seasons. Linseed and noug seed cake had the highest CP, and wheat bran had the lowest CP during both the dry and wet seasons (Tables 2 and 4).

3.3. Mitigation Potential of the Major Feed Resources

3.3.1. *In vitro* total gas production of the major feed resources

Gas production for all crop residues and natural pastures increases over 96 hours of incubation (Fig. 1). Among the identified major feed resources, hay, natural pasture, and oat straw showed high gas production after 3 to 12 hours of incubation, while teff, wheat, and barley straw showed low gas production. Similarly, hay, barley, and teff straw showed the highest gas production at 24 to 96 hours of incubation, while bean straw, wheat straw, and natural pasture showed low gas production among the major feed resources studied. Likewise, wheat bran had the highest gas volume among supplementary feeds ($p < 0.05$) over all incubation periods (Fig. 1).

Table 5
Seasonal *in vitro* gas production (ml/200 mg DM) of major feed resources in central Ethiopia

Type of feeds	Incubation time (hours)														
	3		6		9		12		24		48		72		9
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	I
Crop residues and natural pastures															
Barley straw	6.00^{b}	10.33^{a}	9.93^{b}	13.78^{a}	13.90^{b}	17.22^{a}	17.86	21.44	37.28	37.02	46.73^{b}	51.61^{a}	53.61^{b}	56.58^{a}	5
Bean straw	2.00^{b}	13.81^{a}	5.93^{b}	21.20^{a}	8.39^{b}	26.62^{a}	11.35^{b}	28.88^{a}	31.01	30.83	33.10^{b}	40.42^{a}	34.06^{b}	45.84^{a}	3
Hay	6.92^{b}	13.78^{a}	11.36^{b}	19.68^{a}	16.30^{b}	25.10^{a}	22.22	29.81	40.66	41.28	53.13	54.81	59.26	60.52	6
Natural Pasture	13.81^{a}	6.27^{b}	21.20^{a}	8.96^{b}	26.62^{a}	13.14^{b}	28.88^{a}	15.13^{b}	44.53^{a}	40.38^{b}	45.30^{a}	41.42^{b}	48.27^{a}	45.35^{b}	5
Oat straw	8.92^{b}	12.79^{a}	12.89^{b}	17.71^{a}	15.86^{b}	22.13^{a}	18.83^{b}	35.23^{a}	32.51	33.24	47.57	49.17	52.52	52.14	5
Teff straw	4.45^{b}	6.87^{a}	8.41	9.82	11.87	13.26	15.83	16.98	33.31	32.45	46.15	48.46	55.90	56.45	5
Wheat straw	6.0^{b}	10.31^{a}	10.43^{b}	13.26^{a}	13.90^{b}	17.18^{a}	17.87	20.42	28.93	29.13	30.92^{b}	51.13^{a}	35.34^{b}	56.59^{a}	4
SE	**0.64**	**0.64**	**0.93**	**0.93**	**1.15**	**1.15**	**3.77**	**3.77**	**0.70**	**0.70**	**1.04**	**1.04**	**1.34**	**1.34**	1
Supplementary feed															
Atela	5.93^{b}	12.30^{a}	8.89^{b}	17.71^{a}	12.34^{b}	21.15^{a}	15.29^{b}	23.90^{a}	24.04^{b}	27.31^{a}	26.62^{b}	36.89^{a}	28.60^{b}	41.81^{a}	3
Compound feed	9.88^{b}	18.17^{a}	14.34^{b}	26.03^{a}	19.77^{b}	31.93^{a}	25.70^{b}	37.62^{a}	41.40	42.94	52.39^{b}	62.38^{a}	56.34^{b}	67.78^{a}	5
Linseed cake	7.96^{b}	21.64^{a}	16.40^{b}	31.97^{a}	21.87^{b}	35.91^{a}	24.85^{b}	37.68^{a}	36.94	38.11	42.79^{b}	46.23^{a}	43.77^{b}	48.71^{a}	4
Noug seed cake	7.89^{b}	20.16^{a}	13.31^{b}	26.06^{a}	18.25^{b}	29.02^{a}	21.20^{b}	30.78^{a}	32.87^{b}	34.71^{a}	38.47^{b}	44.75^{a}	40.94^{b}	47.70^{a}	4
Wheat bran	15.39^{b}	22.19^{a}	25.34^{b}	32.06^{a}	34.28^{b}	39.95^{a}	43.22^{b}	45.67^{a}	51.03^{b}	54.36^{a}	61.65^{b}	65.52^{a}	65.60^{b}	70.00^{a}	6
SE	**1.35**	**1.35**	**1.40**	**1.40**	**1.40**	**1.40**	**1.86**	**1.86**	**0.80**	**0.80**	**3.48**	**3.48**	**3.87**	**3.87**	4

Means in the same row with different superscripts show significant differences ($p < 0.05$).

Significant differences ($p < 0.05$) in the seasonal *in vitro* gas production of major feed resources between the wet and dry seasons are presented in Table 5. However, there was no significant seasonal difference ($p > 0.05$) in gas production of barley and wheat straw at 12 to 24 hours. Similarly, there was no significant difference ($p > 0.05$) in gas production of teff straw from 6–96 hours, hay from 12–96 hours, and oat straw from 24–96 hours, during both dry and wet seasons ($p < 0.05$). Furthermore, there was no significant seasonal change ($p > 0.05$) in the gas production of barley at 96 hours or bean straw, compound feed, and linseed cake at 24 hours. Only bean straw, natural pasture, and wheat straw showed significant differences ($p < 0.05$) between the dry and wet seasons after 96 hours.

3.3.2. Methane emission, concentration, and reduction potential of the major feed resources

The total gas and CH_4 production, as well as the percentage of CH_4 in the total gas produced from the feed samples, are displayed in Table 6. There was a significant difference ($p < 0.05$) in total gas, CH_4 generation, and percentage of CH_4 concentration throughout the crop residues and natural pastures, and supplementary feeds. However, there was no significant seasonal difference ($p > 0.05$) in total gas, CH_4 production, and percentage of CH_4 between oat straw and teff straw. Similarly, there was no significant seasonal difference ($p > 0.05$) in the percentage of CH_4 among hay, bean straw, and teff straw from roughages, as well as between linseed cake and noug seed cake from supplementary feeds.

Gas levels ranged from 29.03 to 42.46 mL after 24 hours of incubation with 0.2 g of crop residues and natural pastures substrate. Wheat bran had the highest total GP_{24} value, while atela had the lowest among supplementary feeds. The total GP_{24} was highest in natural pasture and lowest in wheat straw. However, after 48 hours, hay and bean straw produced the highest and lowest gas, respectively (Fig. 1). In addition, after 24 hours of incubation with 0.2 g of supplementary feed substrate, gas levels ranged between 25.67 and 44.97 mL. Among roughages, hay produced the highest CH_4 (51.89 mL/0.2 g DM incubated), while bean straw produced the lowest (40.25 mL/0.2 g DM). Wheat bran produced the highest CH_4 (47.00 mL/0.2 g DM incubated), while atela produced the lowest (39 mL/0.2 g DM) among supplementary feeds.

Table 6
Means of total gas production (GP), CH_4 production, and concentration (as a proportion of total GP)

Type of feeds	GP_{24}, mL/0.2 g DM	CH_4, mL/0.2 g DM	CH_4 Concentration (%)
Crop residues and natural pasture			
Barley straw	37.15^{c}	44.75^{d}	20.49^{d}
Bean straw	30.92^{e}	40.25^{f}	30.29^{b}
Hay	40.97^{b}	51.89^{a}	26.58^{bc}
Natural pasture	42.46^{a}	50.75^{b}	19.33^{d}
Oat straw	32.87^{d}	41.50^{e}	26.23^{c}
Teff straw	32.88^{d}	42.00^{e}	27.90^{bc}
Wheat straw	29.03^{f}	46.25^{c}	59.24^{a}
SE	**0.49**	**0.26**	**1.75**
Supplementary feed			
Atela	25.67^{e}	39.00^{e}	52.05^{a}
Compound feed	42.17^{b}	45.00^{c}	6.63^{c}
Linseed cake	37.52^{c}	46.50^{b}	23.94^{b}
Noug seed cake	33.79^{d}	41.50^{d}	22.79^{b}
Wheat bran	44.97^{a}	47.00^{a}	4.64^{d}
SE	**0.57**	**0.01**	**1.40**

Lower-case letter in each column indicates significant differences among feed types at $p < 0.05$.

Natural pasture had the lowest methane concentration (19.33%), followed by barley straw (20.49%) and oat straw (26.23%), while wheat straw (59.24%) had the highest concentration compared to other crop residues and natural pasture feed types. Similarly, methane content was much lower in wheat bran (4.64%), followed by compound feed (6.63%), and higher in atela (52.05%) than in other types of supplementary feeds (Table 6).

The seasonal means of total gas production, CH_4 production, and methane concentration between dry and wet seasons varied significantly ($p < 0.05$), as shown in Table 7. However, there was no significant seasonal variation ($p > 0.05$) in the total gas production (GP_{24}) of all crop residues, except the natural pasture between dry and wet seasons. The total gas production (GP_{24}) of compound feed and linseed cake among supplemental feeds did not differ significantly between the dry and wet seasons ($p < 0.05$). Additionally, there was no significant seasonal difference ($p > 0.05$) in the CH_4 concentration (%) of atela, linseed cake, and noug seed cake among supplementary feeds between dry and wet seasons.

Table 7
Seasonal means of total gas production (GP), CH_4 production, and concentration (as a proportion of total GP)

Type of feeds	GP_{24}, mL/0.2 g DM		CH_4, mL/0.2 g DM		CH_4 Concentration (%)	
	Dry	Wet	Dry	Wet	Dry	Wet
Crop residues and natural pasture						
Barley straw	37.28	37.02	41.25^b	48.25^a	10.65^b	30.33^a
Bean straw	31.01	30.83	38.00^b	42.50^a	22.68^b	37.90^a
Hay	40.66	41.28	47.78^b	56.00^a	17.50^b	35.67^a
Natural Pasture	44.53^a	40.38^b	55.00^a	46.50^b	23.50^a	15.16^b
Oat straw	32.51	33.24	40.00^b	43.00^a	23.05^b	29.41^a
Teff straw	33.31	32.45	39.00^b	45.0^a	17.09^b	38.70^a
Wheat straw	28.93	29.13	42.00^b	50.50^a	45.15^b	73.33^a
SE	**0.70**	**0.70**	**0.36**	**0.36**	**2.47**	**2.47**
Supplementary feed						
Atela	24.04^b	27.31^a	37.0^b	41.0^a	53.91	50.19
Compound feed	41.40	42.94	42.0^b	48.0^a	1.46^b	11.80^a
Linseed cake	36.94	38.11	46.0^b	47.0^a	23.36	24.53
Noug seed cake	32.87^b	34.71^a	40.0^b	43.0^a	21.70	23.89
Wheat bran	37.09^b	52.86^a	39.0^b	55.0^a	5.23	4.05
SE	**0.80**	**0.80**	**0.01**	**0.01**	**1.97**	**1.97**

Lower-case letter in each column indicates significant differences between feed types at $p < 0.05$

3.3.3. *In vitro* gas production kinetics parameters of major feed resources

The *in vitro* gas production kinetics parameters for the major feed resources are shown in Table 8. There was a significant difference ($p < 0.05$) in gas production from soluble (a), insoluble fraction (b), potential gas production (a + b), rate of gas production (c), and lag time among the selected major feed resources. However, there was no significant difference ($p > 0.05$) in gas production from the soluble fraction (ml)between barley and wheat straw, as well as among hay, bean, oat, and wheat straws.

Teff straw produced the lowest amount of gas ($p < 0.05$) from the soluble fraction (a) and at the slowest rate (c). Bean straw produced the lowest amount of gas ($p < 0.05$) from both the insoluble fraction (b) and potential gas production (a + b). Similarly, Atela had the lowest ($p < 0.05$) gas production from the insoluble fraction (b), potential gas production (a + b), and gas production rate (c). Bean straw exhibited the extended ($p < 0.05$) lag time, followed by wheat straw among roughages. Similarly, atela had the highest lag time ($p < 0.05$), followed by noug seed cake among the supplementary feeds.

Table 8
In vitro gas production kinetics parameters of major feed resources

Type of feeds	a	b	a + b	c	Lag time
Crop residues and natural pastures					
Barley straw	1.66^{c}	61.03^{b}	62.69^{b}	0.03^{ab}	24.93^{b}
Bean straw	5.14^{b}	38.00^{d}	43.14^{d}	0.04^{a}	30.33^{a}
Hay	3.22^{bc}	60.70^{b}	63.93^{b}	0.04^{a}	20.48^{c}
Natural Pasture	7.38^{a}	48.02^{c}	55.40^{c}	0.03^{ab}	22.68^{bc}
Oat straw	4.59^{b}	49.08^{c}	53.67^{c}	0.04^{a}	21.50^{bc}
Teff straw	-0.47^{d}	69.59^{a}	69.12^{a}	0.02^{b}	24.08^{bc}
Wheat straw	3.34^{bc}	48.26^{c}	51.60^{c}	0.03^{ab}	27.08^{ab}
SE	**0.97**	**2.43**	**2.28**	**0.00**	**2.88**
Supplementary feed					
Atela	6.57^{b}	31.12^{c}	37.68^{c}	0.04^{c}	23.73^{a}
Compound feed	6.91^{b}	58.41^{a}	65.33^{a}	0.05^{bc}	11.48^{bc}
Linseed cake	4.97^{b}	42.35^{b}	47.33^{b}	0.11^{a}	11.28^{bc}
Noug seed cake	10.40^{a}	35.24^{c}	45.65^{b}	0.05^{bc}	16.98^{b}
Wheat bran	5.91^{b}	62.51^{a}	68.42^{a}	0.07^{b}	7.02^{c}
SE	**1.20**	**2.65**	**2.83**	**0.01**	**4.10**

Means in the same column with different superscripts differ significantly ($p < 0.05$). a = gas production from soluble fraction (ml), b = gas production from insoluble fraction (ml), a + b = potential gas production (ml), c = rate of gas production (fraction/h) and lag time (hour).

The soluble fractions (a) in noug seed cake produced the highest gas ($p < 0.05$), whereas linseed cake produced the lowest ($p < 0.05$) compared to other supplementary feeds (Table 8). Among other supplemental feeds, linseed cake produced the highest rate of gas generation (c) ($p < 0.05$). Atela had the lowest ($p < 0.05$) gas production from the insoluble fraction (b), potential gas production (a + b), and rate of gas production (c). Wheat bran exhibited the shortest lag time ($p < 0.05$), the fastest fermentation rate, and the highest gas production potential (a + b), followed by linseed cake and compound feed (Table 8).

The seasonal *in vitro* gas production kinetics parameters of major feed resources show significant changes ($p < 0.05$) between the wet and dry seasons (Table 9). However, there was no significant seasonal difference ($p > 0.05$) in gas production from the insoluble fraction (b) of oat and teff straws among crop residues, and atela and compound feed among supplementary feeds between the dry and wet seasons. Similarly, there was no significant difference ($p > 0.05$) between the dry and wet seasons in the potential gas production (a + b) of hay and oat straw among roughages, as well as linseed cake, noug seed cake, and wheat bran among supplemental feeds.

Table 9
Seasonal *in vitro* gas production kinetics parameters of major feed resources in central Ethiopia

Type of feeds	a		b		a + b		c		Lag time	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Crop residues and natural pastures										
Barley straw	5.93^{a}	-2.62^{b}	64.84^{a}	57.23^{b}	63.17	62.22	0.04	0.03	23.60	26.25
Bean straw	12.65^{a}	-2.37^{b}	41.89^{a}	34.11^{b}	46.76^{a}	39.53^{b}	0.05	0.04	16.35^{b}	44.30^{a}
Hay	9.75^{a}	-3.30^{b}	66.14^{a}	55.26^{b}	65.01	62.85	0.04	0.03	19.35	21.60
Natural Pasture	2.25^{b}	12.52^{a}	34.00^{b}	62.04^{a}	46.51^{b}	64.29^{a}	0.02^{b}	0.05^{a}	29.15^{a}	16.20^{b}
Oat straw	6.43^{a}	2.76^{b}	50.36	47.80	54.22	53.12	0.05^{a}	0.03^{b}	13.85^{b}	29.15^{a}
Teff straw	2.22^{a}	-3.16^{b}	72.35	66.82	74.57^{a}	63.67^{b}	0.03	0.02	22.10	26.05
Wheat straw	8.16^{a}	-1.49^{b}	64.92^{a}	31.61^{b}	63.43^{a}	39.77^{b}	0.04	0.03	20.20^{b}	33.95^{a}
SE	**1.38**	**1.38**	**3.43**	**3.43**	**3.22**	**3.22**	**0.01**	**0.01**	**4.08**	**4.08**
Supplementary feed										
Atela	10.26^{a}	2.87^{b}	33.22	29.02	43.48^{a}	31.89^{b}	0.04	0.04	23.20	24.25
Compound feed	13.47^{a}	0.36^{b}	58.70	58.13	72.17^{a}	58.49^{b}	0.05	0.04	8.45	14.50
Linseed cake	7.69^{a}	2.26^{b}	49.14^{a}	35.58^{b}	51.40	43.26	0.18	0.05	5.80	16.75
Noug seed cake	18.37^{a}	2.44^{b}	40.09^{a}	30.40^{b}	48.77	42.53	0.06	0.05	11.85	22.10
Wheat bran	11.27^{a}	0.55^{b}	71.32^{a}	53.71^{b}	71.87	64.98	0.09	0.06	5.35	8.70
SE	**1.69**	**1.69**	**3.74**	**3.74**	**4.00**	**4.00**	**0.02**	**0.02**	**5.80**	**5.80**

Means in the same column with different superscripts differ significantly ($p < 0.05$). a = gas production from soluble fraction (ml), b = gas production from insoluble fraction (ml), a + b = potential gas production (ml), c = rate of gas production (fraction/h) and lag time (h).

Furthermore, there was no significant difference ($p > 0.05$) in the rate of gas production (c) of barley, bean, teff, and wheat straws, as well as hay, among roughages, and all supplementary feeds between the dry and wet seasons. Similarly, there was no significant difference ($p > 0.05$) in lag time for barley straw, teff straw, and hay among roughages, and all supplementary feeds between the dry and wet seasons.

3.4. Correlation between Chemical Compositions, Nutritive Values, and CH_4 Production

The correlation coefficients (r) between CH_4 gas emission, CH_4 concentration, gas production parameters, chemical composition, and nutritive values of the identified major feed resources are displayed in Table 10. Methane emissions (CH_4) showed a positive and significant correlation ($p < 0.05$) with cell wall (NDF, ADF, and ADL), but a negative and significant correlation ($p < 0.05$) with DM, CP, IVOMD, and ME, as well as a negative correlation with ash and EE.

Methane concentration had a positive and significant correlation ($p < 0.001$) with cell wall (NDF, ADF, and ADL), but a negative and significant correlation ($p < 0.001$) with IVOMD and ME. In addition, methane concentration was positively correlated with CH_4 and negatively correlated with DM, ash, CP, and EE (Table 10). Gas production from soluble fractions (a) was positively and significantly correlated ($p < 0.01$) with DM, ash, CP, and EE, while negatively and significantly correlated ($p < 0.05$) with cell wall (NDF, ADF, and ADL), CH4 ($p < 0.001$), and methane concentration ($p < 0.01$). However, it was positively correlated with IVOMD and ME contents. Gas production from insoluble fractions (b) was positively and significantly correlated with NDF, ADF, and AD ($p < 0.01$) and CH_4 ($p < 0.001$). However, it was negatively and significantly correlated with CP ($p < 0.001$), DM, ash, EE ($p < 0.05$), and gas production from soluble fractions ($p < 0.001$). Similarly, it was positively correlated with IVOMD and ME, and negatively correlated with methane concentration.

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Table 10
Correlation coefficient between chemical composition, nutritive values, and CH_4 emission, concentration, *in vitro* gas production kinetics parameters of

No.	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13
1.	**DM**	**1.00**												
2.	Ash	0.20	1.00											
3.	CP	0.28*	0.01	1.00										
4.	EE	0.38*	0.33*	0.83***	1.00									
5.	NDF	-0.24	-0.01	-0.80***	-0.66***	1.00								
6.	ADF	-0.16	-0.02	-0.72***	-0.45**	0.78***	1.00							
7.	ADL	-0.02	-0.28*	-0.02*	-0.07*	0.03*	0.48**	1.00						
8.	IVOMD	0.05	0.03	0.55***	0.45**	-0.62***	-0.67*	-0.08*	1.00					
9.	ME	0.02	0.05	0.48***	0.39**	-0.57***	-0.64***	-0.08*	0.99***	1.00				
10.	CH_4	-0.21*	-0.23	-0.24*	-0.27	0.25*	0.21*	0.31*	-0.31*	-0.36*	1.00			
11.	CH_4 Conc.	-0.06	-0.20	-0.15	-0.21	0.41***	0.46***	0.27***	-0.74***	-0.76***	0.06	1.00		
12.	a	0.46**	0.34**	0.41**	0.50**	-0.42*	-0.37*	-0.21*	0.21	0.18	-0.53***	-0.36**	1.00	
13.	b	-0.40*	-0.06*	-0.49***	-0.48*	0.38**	0.17**	0.19**	0.15	0.21	0.56***	-0.19	-0.59***	1.00
14.	a + b	-0.14	-0.29*	-0.31*	-0.17	0.12	0.16	0.58	0.27*	0.32*	0.06	-0.60***	0.13	0.48***
15.	c	0.23	0.01	0.60***	0.63***	-0.59***	-0.47***	-0.08***	0.50***	0.46***	-0.06	-0.27	0.27*	-0.27*
16.	Lag time	-0.03	-0.47***	-0.14	-0.36*	0.34*	0.24*	0.23*	-0.51**	-0.51**	-0.08	0.57***	-0.37**	-0.17

DM = Dry matter, CP = Crude protein, EE = Ether Extract, NDF = Neutral detergent fiber, ADF = Acid detergent fiber, ADL = Acid detergent lignin, IVOMD = *In vitro* digestibility, ME = Metabolizable energy, CH_4 = Methane, CH_4 Conc.= Methane concentration, a = gas production from soluble fraction, b = gas production fro b = potential gas production, c = rate of gas production. * = p < 0.05, ** = p < 0.01, *** = p < 0.001

There was a significant negative correlation between potential gas production (a + b) and CP, ash ($p < 0.05$), and methane concentration ($p < 0.001$). However, a significant positive correlation was observed between potential gas production (a + b) and gas production from insoluble fractions ($p < 0.001$), IVOMD, and ME ($p < 0.05$) of the major feed resources in the study areas. Similarly, it correlated positively with gas production from soluble fractions (a), NDF, ADF, ADL, and CH_4, while negatively with DM and EE contents

The rate of gas production (c) was positively and significantly correlated with CP, EE, IVOMD, and ME ($p < 0.001$), as well as gas production from soluble fractions ($p < 0.05$). However, there was a negative and significant correlation ($p < 0.001$) with NDF, ADF, ADL, and gas production from insoluble fractions ($p < 0.05$). In addition, it was positively correlated with DM and ash, but negatively with CH_4 and methane concentration. Lag time (hour) was positively and significantly correlated ($p < 0.05$) with cell wall (NDF, ADF, and ADL), and CH_4 concentration ($p < 0.001$), while negatively and significantly correlated with ash ($p < 0.001$), EE ($p < 0.05$), IVOMD, ME, gas production from soluble fractions, the rate of gas production ($p < 0.01$), and potential gas production ($p < 0.001$). Similarly, Lag time (hour) had a negative correlation with DM, CP, CH_4, and gas production from insoluble fractions (b).

4. Discussion

4.1. Chemical Composition and Nutritive Values of Crop Residues and Natural Pastures

The DM contents varied significantly ($p < 0.05$) among crop residues and natural pastures. This significant difference in the chemical composition of different feeds allows users to formulate rations based on the productive performance of the target animals. Crop residues are likely to remain a significant component of ruminant feeds in many parts of Ethiopia as farming expands and grazing resources decline (Duncan et al., 2016). Natural pasture and bean straw had the highest ($p < 0.05$) CP content, whereas wheat, barley, and teff straw had the lowest ($p < 0.05$). In contrast to the current study, Feyisa et al. (2021) revealed a greater crude protein (9.2%) content of natural pasture in Ethiopia's highlands. Similarly, Fekadu (2019) also found the highest concentration of CP for teff, barley, wheat, oats, and bean straws. The disparity between these findings could be due to the variety of feed types, soil type, stage of maturity at harvest, agronomic practices, and climate conditions.

Crude protein is a good measure of overall nutritional value. A 7% CP threshold for optimal feed quality has been proposed, below which ruminal fermentation of feeds may be reduced, and animal protein requirements may not be met (Arelovich et al., 2008). According to Waghorn and Clark (2004), feed CP concentrations must exceed 10% of DM for livestock maintenance and about 19% for high-producing dairy cows or young growing animals. In the

present study, except for natural pasture, all crop residues and hay studied had a CP concentration below the critical level (7% requirement) suggested by Arelovich et al. (2008) and Waghorn and Clark (2004).

Natural pasture had higher ADF and ADL levels, while hay had the lowest among roughage feeds. In contrast to the current data, Feyisa et al. (2021) found that barley straw, wheat straw, teff straw, and bean straw in Ethiopia's highlands had the highest average NDF and ADF. Melesse et al. (2023) observed greater CP content for natural pasture, as well as NDF and ADF contents for hay, barley straw, teff straw, and wheat straw. However, the current results were higher than Melesse et al.'s (2023) findings on NDF, ADF, IVOMD, and ME of natural pasture, IVOMD and ME contents of hay, CP, IVOMD, and ME of barley straw, IVOMD contents of Teff straw, and CP contents of wheat straw. Tropical forages are commonly recognized for having higher lignin contents, which can change voluntary intake and the forage's digestibility (Frei, 2013). This can lead to increased energy loss and an increase in CH_4 production per unit of product due to a decrease in animal production efficiency (Shibata and Terada, 2010).

The higher CP concentrations of natural pasture, hay, and bean straw may account for their higher IVOMD and ME content among crop residues and natural pastures. On the other hand, the high NDF and ADF contents of crop residues could be associated with low IVOMD and ME contents (Table 1). Njidda and Oloche (2022) found that NDF, ADF, and ADL all exhibited a negative correlation with *in vitro* organic matter digestibility and metabolizable energy. Despite the high fiber content (NDF, ADF, and ADL), the natural pasture also had high CP, IVOMD, and ME levels. In contrast, there are also cases when fibers, particularly the lignin concentration and digestibility, do not correlate (Moore and Jung, 2001). The chemical composition of the evaluated major feeds is within the range of values reported for similar feeds in Sub-Saharan Africa (Feedipedia, 2012).

Moreover, the differences in the chemical composition of crop residues and natural pasture observed in this study and those reported in other studies can be attributed to differences in varieties (Tolera et al., 2007), growing conditions such as geographic, seasonal, climatic, and soil characteristics (Elseed et al., 2007; Bampidis and Christodulou, 2011), and the proportion of botanical fractions (Agbagla-Dohnani et al., 2001). Similarly, Pascual et al. (2000) found that feed chemical composition varies with genotypic features, ambient conditions, and plant harvesting stages.

The identified roughages showed lower amounts of ash, CP, and EE during the wet season and higher levels during the dry season ($p < 0.05$), with the exception of natural pasture (natural pasture grazing) feed. This could be attributable to crop residues and hay samples taken shortly after harvest during the dry season. Throughout both seasons, natural pasture was sampled from randomly selected grazing areas. In line with the present findings, Wang et al. (2025) reported that the roughages were mainly hays and straws, which included significant amounts of structural carbohydrates. Plant maturity leads to a significant rise in NDF, ADF, and ADL levels (Kallenbach et al., 2002), but plant age results in increased CP dilution (Gezahagn et al., 2014).

4.2. Chemical composition and Nutritive Values of supplementary feeds

The CP content of all supplementary feeds that were selected for this study was higher than 16.3±0.48 of DM (Table 3). Linseed cake, noug seed cake, and atela had the highest ($p < 0.05$) CP content, whereas compound feed had the lowest ($p < 0.05$). This result is inconsistent with those of Wang et al. (2025), who reported higher (33.87 ± 2.4%) crude protein from different kinds of feedstuffs. Atela had the lowest ($p < 0.05$) ash content, whereas noug seed cake had the highest ($p < 0.05$).

Compound feed, wheat bran, and atela had the lowest ($p < 0.05$) EE content, whereas noug seed cake and linseed cake had the highest ($p < 0.05$). Wang et al. (2025) also found a lower crude fat (6.61 ± 0.77% DM) in various feedstuffs compared to the current results for noug seed cake (9.2± 0.19) and linseed cake (7.4± 0.19). The high content of crude fat (EE) in current protein feeds like noug seed cake and linseed cake could be attributed to the inclusion of numerous byproducts from the oil industry.

The other frequently utilized feed quality measures are the NDF, ADF, and ADL contents. According to Harper and McNeill (2015), NDF content below 35.5% is regarded as a good quality feed, whereas content beyond 46% is considered poor. Linseed cake (27.6±0.70) and compound feed (35.3±0.70) both had NDF values lower than the criterion. These feeds also exhibited lower concentrations of ADF and ADL. The NDF level of noug seed cake and wheat bran did not exceed the poor-quality feed criterion. A low ADF and ADL content can be considered advantageous to feed quality because lower ADF and ADL levels indicate better digestion (Dasci and Comakli, 2011). In addition, Nguku et al. (2016) also reported that the cellulose digestibility reduces with increased lignin content.

Wheat bran, linseed cake, and compound feed exhibited significantly ($p < 0.05$) higher IVOMD and ME concentrations compared to other feed types. The CP, IVOMD, ME, and ADL contents of noug cake in this study were slightly lower; however, the NDF and ADF were higher than those reported in the central highlands of Ethiopia by Fekede et al. (2015). Similarly, the ash, NDF, ADF, ADL, IVOMD, and ME contents of linseed cake in this study were comparably lower; however, the DM and CP were greater than the findings reported in Ethiopia's central highlands by Fekede et al. (2015). Variations in the chemical composition of noug seed cake and linseed cakes could be attributed to factors such as oil extraction efficiency, management practices, and other environmental conditions.

The DM, CP, ADF, ADL, IVOMD, and ME levels recorded for wheat bran in this study were nearly similar, whereas the NDF was lower than those reported by Fekede et al. (2015). The CP and ash contents of atela in this study were comparable, but the DM, NDF, ADF, ADL, IVOMD, and ME were lower than those reported by the same authors. Correspondingly, this study's CP, NDF, ADF, IVOMD, and ME contents of wheat bran, CP and NDF of Atela, NDF and ME contents of linseed cake, and CP, IVOMD, and ME contents of compound feed were comparable to Melesse et al.'s (2023) early findings. However, they revealed greater IVOMD and ME contents of atela, CP and IVOMD contents of linseed cake, CP content of noug seed cake, and higher NDF and ADF contents of compound feed in different parts of Ethiopia. According to Evitayani *et al*. (2004), forages with an organic matter digestibility of more than 50% have a high potential for supplying ME. Therefore, the current study's findings, which obtained a high IVOMD, have great potential to supply the ME needed for dairy cattle production (Tables 1 and 3). A feed's nutritive value is influenced by the concentration of its chemical compositions, as well as the rate and extent of digestion (Getachew et al. 2004).

Evaluating the chemical composition of feed allows for more specific information on the quantitative aspect of the feed materials' chemical elements, both good and undesired (FAO, 2014). Chemical analysis results are more meaningful if they are supported by digestibility studies, because high nutrient composition does not always imply higher nutritive value, as the ingredients detected in the feed may not be digested and utilized by the animals due to digestibility and availability-limiting factors in the feed materials themselves (McDonald et al., 2021).

The current study found a significant increase ($p < 0.05$) in major feed contents of NDF, ADF, and ADL with prolonged days of storage from the dry to wet season. Overall, the means of each chemical composition of the selected roughages, supplementary feed (protein and energy sources), were found within the ranges of previously reported values of Fekadu et al. (2010), ILRI (2021), and Wang et al. (2025).

4.3. Mitigation Potential of the Major Feed Resources

4.3.1. *In vitro* total gas production of the major feed resources

Gas production for all crop residues and natural pastures increases over a 96-hour incubation period. Similarly, the *in vitro* gas production of supplementary feed (energy and protein sources) increased along the incubation period, reaching a maximum at 96 hours. The gas production process is directly related to the substrate's chemical composition and physical structure (Wang et al., 2025).

Hay produced the highest gas volume ($p < 0.05$) during all incubation times. The reason for this could be that hay contains a significant amount of degradable fiber, which encourages microbial fermentation, resulting in gas production *in vitro*. Gas production is a function of fermentable carbohydrate; hence, the volume and rate depend on the nature of the carbohydrate. Wheat bran had the largest gas volume across supplementary feeds ($p < 0.05$) throughout all incubation durations. This could be because wheat bran contains a high concentration of fast-fermentable carbohydrates, particularly starch and arabinoxylan, which are easily broken down by rumen microorganisms, resulting in a high rate of gas production. Wang et al. (2025) found that gas production from energy feeds was much higher than that from other proteins and roughages, which supports the current findings.

Generally, hay and wheat bran produced the highest gas volume at the fastest rate throughout the incubation period. In terms of the current study's implications, the feed types with the highest rapidly fermentable proportion would have the fastest constant rate of gas production and the shortest feasible lag time. In contrast, the feed types with the highest insoluble but timely fermentable proportion would have the slowest rate of gas production constant and the longest possible lag time (Table 8).

Teff straw and bean straw had the lowest gas volumes ($p < 0.05$) during the 3–12 and after 24–96-hour incubation periods, respectively. However, atela produced the lowest gas volume ($p < 0.05$) throughout the incubation period (Fig. 1). This could be due to its high concentration of lignocellulosic material, which is less digestible and provides fewer readily fermentable carbohydrates or slowly fermentable nutrients than other substrates, as well as its considerable protein content, which can impede overall fermentation and cause it to produce the lowest amount of gas during incubation.

In vitro fermentation proceeds more slowly and produces less gas because the brewing process itself eliminates a large portion of the fermentable sugars, leaving behind a residue that is mostly made up of fiber and protein (Mussatto et al., 2006). During the first 12 hours of incubation, all identified feed resources produced less *in vitro* gas volume. Gas production for compound feed, wheat bran, hay, barley straw, and teff straw increased significantly from 24 to 96 hours (Fig. 1).

In the current study, the total volume of gas production increased with increasing time of incubation (Fig. 1). The gas production pattern in this study revealed that more dry matter fermentation was still possible up to 96 hours for all major feed resources, and there was no termination of fermentation before 96 hours of incubation. After 96 hours of incubation, gas production ranged between 38 and 71 ml/200mg DM, which was higher than the early finding of Amsalu et al. (2018), who reported a range of 12 to 56 ml/200mg DM. Maheri-Sis et al. (2008) found that feeds with lower NDF and ADF levels produced more *in vitro* gas, which is consistent with current findings of moderate NDF, ADF, and ADL levels in hay and wheat bran, which produced more *in vitro* gas than other feeds (Tables 1 and 3).

Gas production from hay and wheat bran increased at an accelerating rate until 24 hours of incubation, after which it slowed down. The initial increase in gas production may be due to the rapid fermentation of readily available carbohydrates by rumen microorganisms. However, after about 24 hours, the rate of gas production decreases as the easily digestible carbohydrates are depleted, causing the microorganisms to shift to fermenting slower-digesting fiber components such as cellulose and hemicellulose. This slower fermentation of more complex carbohydrates results in a reduced gas production rate, even though total gas production continues to rise. In line with the current findings, Cone and van Gelder (1999), as cited in Gelgelo et al. (2023), reported that the immediately fermentable fractions of a feed had rapid initial gas production, which decreased with subsequent incubations. Gelgelo et al. (2023) also highlighted that the largest significant gas production observed for forage species at early incubation hours may be indicative of a higher soluble nutrient composition. According to Amsalu et al. (2018), the browse's high CP concentration and low fermentable carbohydrates or high non-fermentable cell wall (ADL and ash) contents may have contributed to the first increase in gas production.

Seasonal differences in *in vitro* gas production were significant ($p < 0.05$), with the wet season showing higher levels than the dry season, except in natural pastures (Table 5). Wet season observations show that the most potent gas production occurs during the incubation stage. These findings are consistent with those of Gelgelo et al. (2023), who found that season had a significant ($p < 0.001$) impact on *in vitro* gas and methane production as well as the methane to total gas ratio, with the wet season showing the highest observations compared to the dry season. The significant differences detected in *in vitro* gas production parameters between seasons indicated the presence of evident nutritional variability among major feed resources at different times of the year in the study area. Overall, the majority of protein and roughage feeds in the present study produced less gas and had a smaller volume than energy feeds (Fig. 1 and Table 5). Because structural carbohydrates are more resistant to degradation, they can significantly impact gas volume and production rate (Wang et al., 2025).

4.3.2. Methane emission, concentration, and reduction potential of the major feed resources

Hay produced the highest CH_4, whereas bean straw produced the lowest among the roughages. Similarly, wheat bran produced the greatest CH_4, whereas atela produced the lowest among supplementary feeds. The observed disparity in CH_4 emissions among the feed samples could be due to variances in fiber content. Methane production represents the efficiency of microbial fermentation in the rumen and is associated with high levels of structural carbohydrates (Jayanegara et al., 2009). As a result, the high potency of natural pasture, hay, and wheat bran in methane production may indicate a higher content of highly digestible carbohydrate components. Remesy *et al*. (1995), as cited in Amsalu et al. (2018), found that increased gas production can considerably contribute to energy supply via short-chain fatty acid production.

The CH_4 concentration (as a proportion of total GP) in feed samples varied significantly ($p < 0.05$), ranging from 19.33 for natural pasture to 59.24 for wheat straw among roughages, and 4.64 for wheat bran to 52.05 for atela among supplementary feeds. This result contradicts the early findings of Berhanu et al. (2019), who found that forage species had lower CH_4 concentration, ranging from 16.25 to 52.22% compared to crop residues and natural pasture feed types. Undoubtedly, high methane production results in significant energy loss for animals and contributes to greenhouse gas emissions in the environment (Moss et al., 2000).

The ratio of methane to total gas production, which is an indicator of a given fodder species' methanogenic properties per unit of degraded nutrient, is primarily used as an objective criterion for screening out forage species for ruminant nutrition (Bezabih et al., 2013), taking into account both the nutritional and environmental implications of CH_4 emissions. A low value of this ratio indicates that the most soluble fractions of a feed material have a low methane-producing potential, meaning that less methane is produced per unit of net gas volume (Moss et al., 2000).

The proportion of methane in total gas could be utilized to determine the plant's capacity to reduce CH_4 production *in vitro* (Lopez et al., 2010; Bhatta et al., 2012). Therefore, lower CH_4 to gas percentages indicate that a particular candidate (hay, natural pasture, and wheat bran) would be more effective as a rumen modification for CH_4 reduction than those with higher percentages. In the current study, natural pasture and wheat bran had the highest CH_4 reduction potential. Barley straw and oat straw from crop residues, along with compound feeds from supplementary feeds, consistently showed a lower CH_4 percentage, making them promising options to reduce CH_4 production in ruminants in the study area. That means, they can be promoted as valuable feed sources for dairy cattle while simultaneously reducing the CH_4 emissions. Feeds with a greater CP content have been associated with lower CH_4 production (Table 1–4), making them an ideal source of protein supplement in dairy cattle feed.

Methane production in major feeds increased significantly ($p < 0.05$) from dry to wet seasons, with the exception of natural pasture from grazing. This could be attributed to the lower digestible nutrients and the relatively higher fibrous and lignified nature of the wet season (Tables 1–4). The current study's significant differences among feed types and the higher record of methane production during the wet season compared to the dry season were in line with the findings of Tsegaye et al. (2019), which may be a reflection of the impact of season on the nutritive potential of feed types previously reported (Marius et al., 2021).

4.3.3. *In vitro* gas production kinetics parameters of major feed resources

Gas production from soluble fractions(a) in natural pasture was the highest ($p < 0.05$) among roughages. Teff straw produced the most gas from both insoluble fractions (b) and potential gas (a + b) production ($p < 0.05$) among roughages (Table 8). The longest ($p < 0.05$) lag time was observed for bean straw, followed by wheat straw among roughages. This might be due to bean straw having a higher lignin concentration (Table 1) and a more rigid fiber structure, which considerably delays the start of fermentation and microbial colonization, resulting in a longer lag period.

The lowest gas production ($p < 0.05$) from the soluble fraction (a) and the lowest rate of gas production (c) were observed from teff straw. Likewise, the lowest gas production ($p < 0.05$) from the insoluble fraction (b) and potential gas production (a + b) were observed from bean straw. The shortest ($p < 0.05$) lag time, fastest fermentation rate, and relatively highest ($p < 0.05$) gas production potential were observed for hay, followed by oat straw and natural pasture. These results suggest that rumen microorganisms were able to make better use of the feed, most likely due to its higher fermentable nutrients.

The soluble fractions (a) in noug seed cake produced the most gas ($p < 0.05$) compared to other supplementary feeds. Wheat bran produced the highest gas from insoluble fractions (b) and potential gas (a + b) production ($p < 0.05$), followed by compound feed as supplementary feed. This higher potential gas production (a + b) can greatly contribute to energy supply through short-chain fatty acid production (Table 3). Generally, bean straw and atela may have the greatest lag times because of their negative correlation with *in vitro* gas production kinetics parameters of the major feed resources (Table 10). Consistent with this, Tolera and Sundstøl (1999) found that poorly digested feed components need time to be hydrated and colonized by rumen microbes before fermentation.

The lowest gas production ($p < 0.05$) from the insoluble fraction (b), potential gas production (a + b), and the lowest rate of gas production (c) were observed from atela. This could be due to the extraction of readily available and highly fermentable carbohydrates, such as simple sugars and starches, from grain to produce beer; the remaining lignocellulosic material has a high moisture content and a high concentration of structural components such as cellulose, hemicellulose, and lignin, which are difficult for microorganisms to ferment, resulting in lower gas production.

Wheat bran had the shortest ($p < 0.05$) lag time, fastest fermentation rate, and relatively the highest gas production potential (a + b), followed by linseed cake and compound feed. This could be due to its moderate cell wall contents (NDF, ADF, ADL), which indicate better nutrient availability for rumen microorganisms (Table 3). Therefore, these qualities make wheat bran a promising supplement to low-quality roughages. This result is consistent with the findings of Khazaal *et al*. (1993), as quoted in Amsalu et al. (2018), who reported that feed degradability affects potential gas production (a + b).

Significant differences ($p < 0.05$) in the seasonal *in vitro* gas production kinetics parameters of major feed resources between the wet and dry seasons are shown in Table 9. This could be due to the concentration of soluble carbohydrates in the feeds. Table 9 reveals that, with the exception of natural pasture, gas production from *in vitro* gas production kinetics parameters such as gas production from soluble fraction (a), gas production from insoluble fraction (b), potential gas production (a + b), and rate of gas production (c) were frequently higher in the dry season ($p < 0.05$) than in the wet season for both crop residues and supplemental feeds. This may be because feeds with higher protein content and lower fiber (NDF, ADF, and lignin) during the dry season have a higher nutritional value than fibrous, less digestible material available during the wet season, which leads to more effective and greater overall gas production. The findings of Tsegaye et al. (2019) are consistent with the significant variability in *in vitro* gas production kinetics of major feed resources with varying seasons observed in the current study, which was an indicator of the predicted difference in digestibility and nutritional quality of different feed types at different seasons of the year.

The natural pasture was sampled directly from the grazing land during both wet and dry seasons. As a result, during the wet season, the pasture was younger, had higher crude protein, ME, and IVOMD levels, fermentation was generally faster, and the time before fermentation began was often shorter due to the readily available soluble carbohydrates and lower fiber content, which microbes could use immediately (Table 2). In line with the current findings, Woretaw and Beyero (2022) found that pastures had higher fiber fractions and fewer soluble nutrients in the dry season than in the wet season due to increased maturity and low soil moisture. The NDF, ADF, and lignin content of the feeds may account for the seasonal differences in the lag time by delaying the start of nutrient degradation in the rumen (Fievez et al., 2005).

4.4. Relationship between Chemical Compositions and Nutritive Values, and CH_4 Production

Methane emissions (CH_4) showed a negative and significant correlation ($p < 0.05$) with DM, CP, IVOMD, and ME, as well as a negative correlation with ash and EE, but a positive and significant correlation ($p < 0.05$) with NDF, ADF, and ADL. Tırınk et al. (2022) and Osafo et al. (2023) found significant negative correlations between ME and NDF, ADF, and ADL, along with a strong positive correlation between CP content in animal feeds, which aligns with current findings. Consistent with this, Shibata and Terada (2010) reported that methane emissions decrease as the protein level of the feed increases and increase as fiber content increases. They also observed that in lactating cows, CH_4 emission per kg dry matter intake (DMI) was 35% higher with high-roughage, lower-digestibility diets compared to high-concentrate, higher-digestibility diets. The negative correlation between CP and methane production aligns with Moss's (2000) findings.

Furthermore, the negative correlations between methane production and ash and ether extract support previous findings by Yan et al. (2009) and Ellis et al. (2008), respectively. The study found a positive correlation between methane production and cell-wall contents (NDF, ADF, cellulose, and lignin), which is consistent with previous findings (Moss 2000; Singh et al., 2012). The present study found a positive correlation between ADL and CH_4 release, which contradicts previous findings by Hindrichsen et al. (2004), Singh et al. (2011), and Berhanu et al. (2019). The reported negative effects of ADL on CH_4 production point to lignin's good involvement in lowering CH_4 emissions from ruminant production (Dasci and Comakli, 2011). Despite this unusual discovery of lignin's favorable benefits, nutritionists typically recommend reducing the lignin concentration of ruminant feeds (Moore and Jung, 2001).

Gas production from soluble fractions (a) showed a negative and significant correlation ($p < 0.05$) with cell wall (NDF, ADF, and ADL), CH4 ($p < 0.001$), and methane concentration ($p < 0.01$), but a positive and significant correlation ($p < 0.01$) with DM, ash, CP, and EE. Consistent with the present findings, Amsalu et al. (2018) revealed that gas production from soluble fractions (a) had a positive and significant ($P < 0.001$) correlation with CP and a negative correlation with cell wall (NDF, ADF, and ADL), as well as a negative and significant ($p < 0.001$) correlation between gas production from insoluble fractions (b) and ADF contents of the browse species.

Potential gas production (a + b) showed a significant negative correlation with CP, ash ($p < 0.05$), and methane concentration ($P < 0.001$). In agreement with the current findings, Getachew et al. (2004) found a significant negative correlation between CP content and potential gas production. The current study's positive and significant correlation between CP, gas production from soluble fractions (a), and rate of gas production (c) is consistent with the findings of Amsalu et al. (2018). This positive and significant correlation between gas production from soluble fractions (a) and CP may imply that CP contributes significantly to the rapidly fermentable fractions of total dry matter.

The current findings found a positive correlation between potential gas production (a + b) and gas production from insoluble fraction (b), NDF, ADF, and ADL contents of feed resources, which were comparable with the report of Abdulrazak et al. (2000). However, these findings contradicted those of Getachew et al. (2004) and Kulivand and Kafilzadeh (2015), who revealed a negative correlation between potential gas production (a + b) and both NDF and ADF levels in several ruminant feeds.

IVOMD and ME contents had a negative and significant correlation with the NDF, ADF, and ADL of the selected major feeds in the study areas. Theart et al. (2015) found a negative association between NDF, ADF, and lignin and *in vitro* digestibility, which is consistent with the current findings. In general, CP contents correlated negatively and significantly with NDF, ADF, ADL, methane gas emissions, methane gas concentration, gas production from insoluble fractions (b), and potential gas production (a + b). Similarly, it showed a positive and strongly significant correlation with EE, IVOMD, ME, gas production from soluble fractions (a), and gas production rate. This result is consistent with those of Parissi et al. (2005), Karabulut et al. (2007), and Osafo et al. (2023), who revealed a positive correlation between CP, ME, and OMD for tropical forages with high CP content. Consistent with present findings, Getachew et al. (2004) also found that crude protein (CP) had a negative correlation with gas production from insoluble fractions (b) and a positive correlation with gas production rate (c).

Conclusions

In this study, there were significant differences ($p < 0.05$) in the chemical composition, nutritive value, and *in vitro* gas and methane production of the major feed resources during the wet and dry seasons. The relatively high CP content of natural pasture, hay, and bean straw suggests that these feed sources have higher IVOMD and ME. Conversely, low IVOMD and ME levels may be associated with crop residues' high NDF and ADF contents. All supplementary feeds had high CP values, making them suitable as high-protein and energy sources to supplement low-quality roughages. In the current study, natural pasture and wheat bran showed the greatest CH_4 reduction capacity. In addition, barley straw and oat straw from crop residues, as well as compound feeds from supplementary feeds, consistently had reduced CH_4 percentages, making them promising opportunities for mitigating CH_4 production in ruminants in the study area.

The current study's findings revealed that methane production varied across the identified major feed resources, indicating that feed resources can be screened for decreased methane production. The negative correlation between methane production and CP, IVOMD, and ME suggests that screening and selecting the feed types with higher CP content can help to mitigate methane production in central Ethiopia. The sighting that the most palatable major feed resources produced low to medium methane levels may indicate that high-quality feeds are beneficial for methane mitigation. Furthermore, when developing a dairy cattle ration, using feeds with lower methane production may have the potential to reduce methane emissions from the dairy sector. However, additional nutritional studies, such as secondary metabolites and in vivo experiments, are needed to strengthen the study's conclusions.

Declarations

CRediT authorship contribution statement

Teshome Gemechu: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mitiku Eshetu:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition. **Yesihak Yusuf Mummed:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology. **Ulfina Galmessa:** Writing – review & editing, Validation, Supervision, Methodology. **Aemiro Kehaliew:** Writing – review & editing, Validation, Supervision, Methodology

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Clinical trial declarations

Not applicable

Ethics decelerations

Ethics approval and consent to participate:

This study received ethical approval from the School of Animal Sciences at Haramaya University on October 3, 2022, with reference number AnSc/256/182/2022. The Institutional Research Ethics Committee of Haramaya University set criteria and guidelines that were followed throughout the entire research process. The study focuses on identifying low-methane-emitting diets with high nutritional value. As a result, the feed types were chosen based on information acquired from household interviews and focus group discussions. Their participation in the study was voluntary, and delicate topics were handled politely. No personally identifying information was requested. Before data collection, all subjects provided informed consent. All research findings were anonymized, and participants were given complete secrecy and anonymity throughout the study.

Consent for publication

Not applicable

Availability of data and material

The corresponding author may make the study's datasets available upon reasonable request.

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Declaration of competing interests

The authors declare that they have no conflicts of interest in publishing this research manuscript.

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Figures

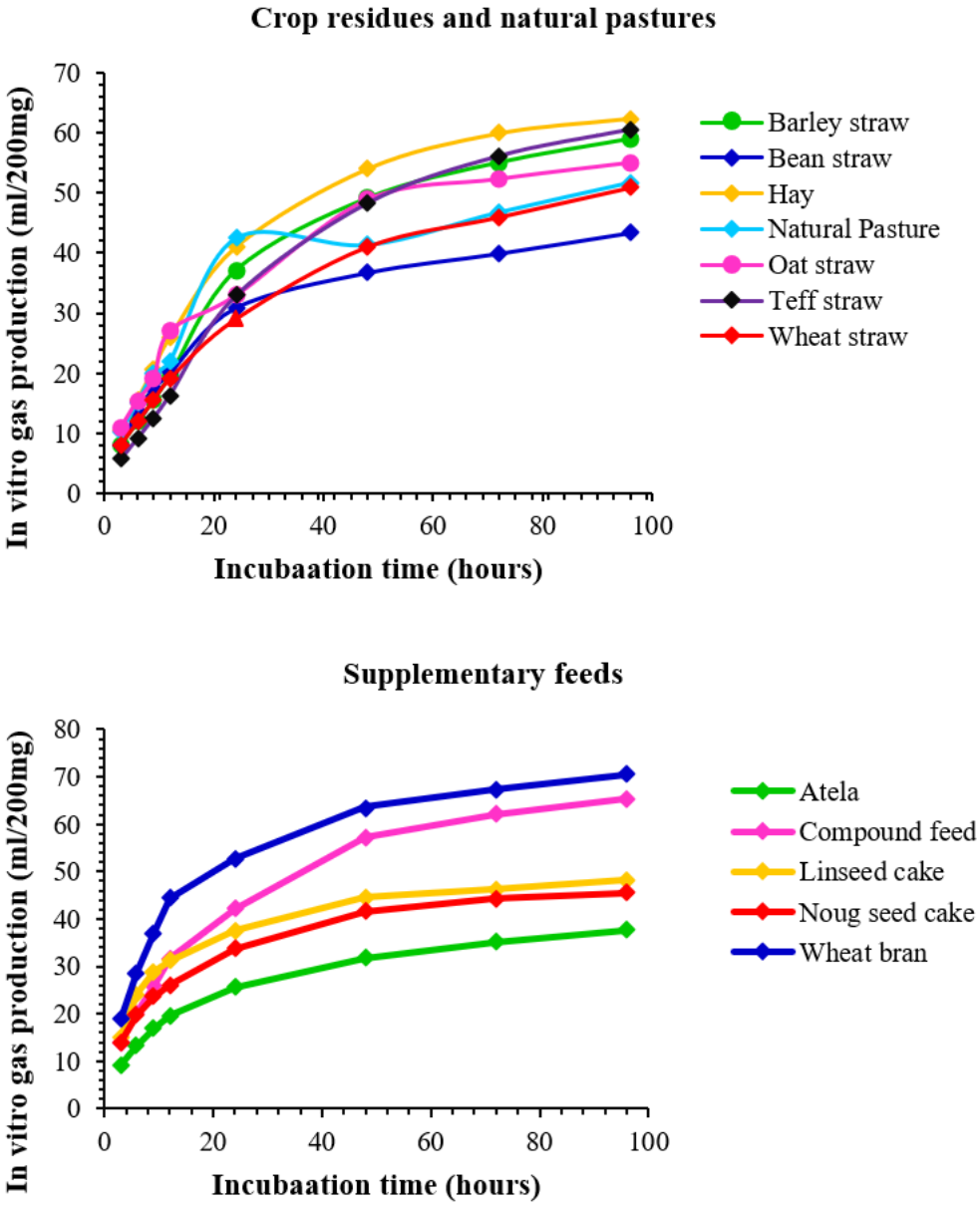


Figure 1

In vitro gas production (ml/200 mg DM) of major feed resources (p-value = 0.05)