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Methane Emissions from Ruminant Livestock in Ethiopia: Promising Forage Species to Reduce CH₄ Emissions

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Abstract: This paper assesses the ability of fodder plants to reduce methane (CH₄) emissions while simultaneously improving animal productivity in Ethiopia. Enteric CH₄ emissions from ruminants in Ethiopia increased by 12% or ≈ 6197 Gg CO₂-eq. in 2017 compared to the year 2011. In this study, six tropical multipurpose forages (*Leucaena leucocephala* (Lam.) de Wit, *Moringa stenopetala* (Bak.f.) Cuf., *Sesbania sesban* (L.) Merr., *Cajanus cajan* (L.) Millsp., *Crotalaria juncea* L., and *Lablab purpureus* L.(Sweet)) and maize stover were characterized in terms of chemical composition, in vitro CH₄ production, and CH₄ concentration (%). The objective was to identify forages with low CH₄ production potential but with adequate forage quality. The forages differed significantly in chemical composition and in enteric CH₄ emission. The dry matter (DM), ash, crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) ranged between 89.4–95.4%, 6.08–12.5%, 3.3–30.7%, 20.4–76.0%, 10.8–44.8, and 2.9–14.1%, respectively. All forage plants, except maize stover, contained high CP content above a threshold value (i.e., 7%). *Cajanus c.* generates the lowest amount of CH₄ (32.83 mL/0.2 g DM incubated). CH₄ concentration (%) was used as a potential indicator to determine the capacity of a plant to lower CH₄ production. Among the studied species, *L. purpureus* showed the highest CH₄ reduction potential (16%) followed by *C. juncea* (23.45%), *M. stenopetala* (24.2%), and *L. leucocephala* (25.5%). *M. stenopetala* was the most frequently preferred by the farmers followed by *C. juncea* and *L. leucocephala*. We concluded that *M. stenopetala*, *C. juncea*, and *L. leucocephala* can be promoted as valuable feed resources for ruminants while simultaneously reducing CH₄ emissions.

Keywords: ruminant livestock; methane emissions; methane reduction; promising forages; farmers' preferences; Ethiopia

1. Introduction

Ethiopia has a tremendous livestock resource, currently estimated at 60 million head of cattle and 61 million sheep and goats, in a variety of production systems ranging from pastoral to mixed crop–livestock systems with different levels of intensification [1]. For developing countries like Ethiopia—where the demand for animal products is expected to rise owing to a growing human population and economic changes [2]—this resource, if managed properly, has great potential to raise food outputs. However, despite the country's large livestock population, the production from livestock

systems in Ethiopia is low, largely because of poor nutrition. The same is true in many tropical regions of the developing world, where a large proportion of the global ruminant population exists [3]. The productivity of ruminants is limited by the low nitrogen and high fibre content of native pastures and crop residues, which form the basis of the diet in these regions [4].

This low productivity not only results in high absolute CH₄ emissions, making developing countries responsible for 75% of global enteric CH₄ emissions but also in high emissions per unit of product [3]. These emissions are of worldwide concern, particularly in countries such as Ethiopia where large populations of ruminants are located (90% of ruminants in Ethiopia) [1] in mixed farming systems. These animals are mainly raised on the grazing of native pastures, aftermath and crop residues and, to a lesser extent, improved fields [5]. Ruminants fed on these types of forages produce more CH₄ (e.g., 1.6 kg CO₂-eq./kg of milk in Eastern and Western Europe) than ruminants fed on high quality forage diets (e.g., 9 kg CO₂-eq./kg of milk in sub Saharan Africa) [6]. Furthermore, CH₄ emissions represent a loss (up to 15%) of digestible energy to the animal as well as a threat to the environment [4].

Greenhouse gas emission in Ethiopia is estimated at 150 Mt CO₂-eq., and represented less than 0.3% of the global emissions in 2010 [7]. Estimates of CH₄ emission (data from The World Bank) indicate that agriculture, almost entirely through livestock, totalled 60.3 MT CO₂-eq. in 2008, which is approximately 71% of the national CH₄ emissions. Given the sizeable ruminant population in the country and the extensive nature of the production systems, the contribution of ruminants to GHG emissions is likely to be much greater than what is currently known. In any case, owing to the rising demand for livestock products, the population of domestic ruminants is likely to increase, which considerably accelerates the increase in GHG emissions [7,8]. Only limited documentation exists, however, regarding CH₄ emissions from the ruminant population in Ethiopia. As a result, limited mitigation efforts are directed toward this sector. It is therefore important to estimate CH₄ emissions to assess the gravity of this problem, and to study mitigation options. In contrast to developed countries, developing countries may be facing challenges that need to be addressed before the environmental burdens of GHG emissions become a priority in their national policies [9].

Ruminant production systems in the developing countries of the tropics are associated with lower feed efficiency and higher emission intensities as a consequence of low productivity, poor nutrition, and animals of low productive potential. In this regard, although mixed crop-livestock systems have low absolute emission per hectare, they produce high emissions per unit of output [3], which also represents an indirect economic loss for the farmers [10].

Given the growing human population and climate change, the principal challenge for developing countries such as Ethiopia is to enhance animal productivity while minimizing the environmental damage caused by livestock. A key to this is reducing CH₄ emissions from ruminants [4]. To this end, supplementing traditional feed resources with planted forages appears to be a simple solution to this problem. Cultivation of improved forage crops is relatively cheaper than purchasing concentrate supplements, more appropriate to the Ethiopian livestock production system, and is also environmentally friendly. Improved forage crops produce a significant amount of quality herbage that, when used in combination with crop residues, improves resource-use efficiency. These crops can also complement crop production by maintaining soil fertility by fixing nitrogen or when used as mulch. Improving the quantity and quality of forage produced will also improve animal feed efficiency, reduce CH₄ emissions per unit of animal product, and lead to production benefits for farmers. In this respect, the use of easily adapted multipurpose forages grown by small-scale farmers might be a potentially efficient way to increase ruminant productivity [11] sustainably.

In Ethiopia over the past five decades, several forage species and accessions have been evaluated in a wide range of agro-ecologies. So far, research on forage plants has been limited to adaptation, biomass, nutritive value, and *in vitro* digestibility [5]. Emphasis has also been placed on correcting the nutritional deficiencies of natural pastures [12] and crop residues [13,14]. The testing of forage plants, whether introduced or locally available for their potential to reduce CH₄ emissions, has received very little attention.

Therefore, we undertook this study (i) to estimate CH₄ production of some selected forage plants and (ii) to identify low CH₄ producing forages with adequate forage quality. The study focused on adapted forages recommended for use in the crop–livestock farming systems of southern Ethiopia and maize stover, a widely used feed for ruminants. In East Africa, especially in highland areas, maize yields although subject to a general lowering are likely to increase, providing more human food and animal feed [15]. This scenario presents an opportunity for greater emphasis on dual purpose food–feed crops such as maize to meet the future challenge of increasing ruminant productivity and sustainability of crop–livestock systems in the country. Although the value of maize residues as fodder is widely recognized, there is less understanding of its effect on enteric CH₄ production. We hypothesized that multipurpose forage species reduce CH₄ production while providing high quality feed to complement lower quality crop residues.

Such analysis will provide the opportunity to help design new management and feed strategies in Ethiopia. This study also quantifies the amount of enteric CH₄ produced from ruminant livestock in the country. Such emission data is essential to inform policy dialogue and avoid oversimplification.

2. Materials and Methods

2.1. Estimating Enteric CH₄ Emissions from Ruminant Livestock

In the current study, we employed a Tier 1 approach of the IPCC [16] for its ease of application (default values) to the Ethiopian context and for its input data requirement (population data for each specific animal category) to estimate enteric CH₄ emissions from the ruminant livestock. We calculated CH₄ emissions for each animal category by multiplying the animal population (number of head) by the average emission factors associated with the specific animal category (Equation (1)) and summed Equation (2). Results were expressed in gigagrams per year (Gg year⁻¹). Data for livestock population was obtained from the annual national livestock and livestock characteristics censuses conducted by the Central Statistical Authority of Ethiopia, which completes population inventories annually in December, in the years 2010/2011 and 2016/2017. These surveys covered all the regions of the country except the nomadic pastoral areas (three zones of Afar and six zones of the Somali region) where livestock population is very low. The livestock population data covered 69 of 78 zones (i.e., 88%) for 2010/2011 and 66 of 75 zones (i.e., 88%) of the country for 2016/2017, respectively. The livestock categories included were dairy cattle, non-dairy cattle (beef cattle, breeding bull, calves, heifers and steers, and other matured cows), sheep, and goats. Almost all the cattle, sheep, and goat breeds kept by smallholders in Ethiopia are indigenous [1].

$$\text{Emissions (CH}_4\text{)}_{(T)} = \text{EF}_{(T)} \times \text{N}_{(T)}/10^6 \quad (1)$$

where:

Emissions (CH₄)_(T) = enteric CH₄ emissions for a defined animal category T, Gg CH₄ year⁻¹

EF_(T) = emission factor for each specific animal category T, kg CH₄ head⁻¹

N_(T) = the number of heads for each specific animal category T in the country

T = category of animal

$$\text{Total CH}_4\text{Enteric} = \sum E_i \quad (2)$$

where:

Total CH₄Enteric = total CH₄ emissions from Enteric Fermentation, Gg CH₄ year⁻¹

E_i = is the emissions for the ith animal categories

2.2. Assessment of Nutritive Value and CH₄ Emission Reduction Potential of Forages

2.2.1. Experimental Plants

Samples of seven forages—three tropical multipurpose trees (*Leucaena leucocephala*, *Moringa stenopetala*, and *Sesbania sesban*), one shrub (*Cajanus cajan*), two legumes (*Crotalaria juncea*, *Lablab purpureus*), and maize stover—that are being used for feeding ruminants in southern Ethiopia were analysed for chemical composition and in vitro CH₄ abatement. We chose all sample forages except maize stover based on (i) their broader use in the farming community, (ii) high biomass production potential, and (iii) adaptation to poor environmental conditions such as poor soils and ability to withstand drought conditions. Samples of palatable forage (i.e., fresh leaves, twigs, tender stems, and/or whole forage) were harvested from 3 individual plants (at a similar stage of physiological maturity at harvest) per each species selected at random. All tree species were planted on one geographical location in July 2014 while the rest of the studied forages were planted during the 2016/2017 growing season. The harvested samples were then pooled for each individual species to form representative samples. Here we have assumed that since samples are taken from individual plants of similar age and physiological status difference between individual plants of same species might be insignificant. Our main interest was to see the average effect of species on the parameters tested under the conditions provided and not on the effect of specific plant (from which we pooled the samples). Samples were oven-dried at 65 °C for 48 hours. Feed samples ground through a 1 mm sieve were used for chemical analyses and in vitro assays.

2.2.2. Chemical Analysis

Samples were analysed for dry matter (DM), ash, and crude protein (CP; N × 6.25) as described by AOAC [17]; neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) according to Van Soest et al. [18] using an ANKOM²⁰⁰ Fiber Analyzer (filter bag technique; ANKOM Technology Corp., Fairport, NY, USA). Both NDF and ADF were expressed exclusive of residual ash, and NDF analysis was without α-amylase and sodium sulfite. Residue from ADF determination was treated with 72% sulfuric acid for ADL estimation. Chemical analysis was in duplicate.

2.2.3. In Vitro Studies

The in vitro gas production technique employed to determine CH₄ production was developed by Menke et al. [19] and modified by Blummel and Ørskov [20] in that feeds are incubated in a thermostatically controlled water bath rather than a rotating incubator.

- Rumen Fluid Collection and Inoculum

Rumen fluid was obtained from two fistulated Adilo sheep (32.9 kg mean body weight) kept indoors and received a roughage-based diet containing mixed mostly grass (ad libitum) and supplemented with 400 g DM of concentrate per day offered in 2 portions. Ruminant fluid was collected before the morning feeding through a suction tube into a pre-warmed thermos flask (39 °C), previously filled with CO₂. The pooled ruminal fluid was strained through 8 layers of gauze, flushed with CO₂ [21], and then mixed with Menke's buffer (incubation medium) in a 1:2 ratio (v/v). The inoculum (rumen fluid + buffer) was prepared using the method described by Menke and Steingass [22].

- Incubation to Determine Gas Production and Methane

About 200 mg of feed sample was incubated in triplicate in 100 mL of glass syringes in 2 separate runs/replications. In both runs, each sample was tested with 3 replications (using 3 syringes) plus 2 blanks (syringes incubated with the inoculum alone). The syringes containing feed samples, pre-warmed at 39 °C and their pistons lubricated with Vaseline to ease movement and prevent gas from escaping, were then inoculated with 30 mL inoculum (10 mL rumen + 20 mL buffer mixture) under continuous CO₂

flushing. They were incubated at 39 °C in a water bath for 48 hours and were shaken manually every hour for an initial 8 h (including 0 h) of incubation [23] and then at each recording time [24]. Gas production was recorded before incubation (0 h) and after 4, 8, 12, 24, and 48 h of incubation. Total gas values were corrected for blank incubation. However, due to the absence of reference standards with known gas values in Ethiopia, there was no correction for standard feed sample.

- Determination of Total Gas, CH₄ Production, and Other Parameters

Total gas production was measured by reading the position of the piston at each time point. Net gas production was calculated by subtracting mean blank values from the volume of gas produced from incubated feeds (Appendix A Annex 1). Methane production was measured at post-incubation period using the procedure described by Fievez et al. [25]. Accordingly, 4 mL of NaOH (10 M) was introduced into the incubated contents in each syringe via a connector (silicon tube) fitted between a syringe containing NaOH solution and the incubation syringe, thereby avoiding gas escape. Then, the incubation syringe was shaken, and the remaining gas volume was recorded. Mixing of the incubated contents with NaOH allowed absorption of CO₂, with the gas volume remaining in the syringe considered CH₄ (Demeyer et al., 1988, cited in Fievez et al. [25]). Test experiments prove that CH₄ volumes measured after absorption of CO₂ from *in vitro* incubations in syringes show consistent results with values in gas chromatography, which was shown for many feedstuffs [25]. The CH₄ concentration (percentage) was determined [26] as:

$$\text{Methane concentration (\%)} = (\text{Net CH}_4 \text{ production} / \text{Net gas production} \times 100) \quad (3)$$

Using CP, ash contents and net gas production (GP) (corrected for blank) at 48 h incubation (GP, mL), *in vitro* organic matter digestibility (OMD %) and metabolizable energy (ME, MJ kg⁻¹ DM) contents of the samples were calculated using equations of Menke and Steingass [22] as

$$\text{OMD (\%)} = 14.88 + 0.889 \text{ GP} + 0.45 \text{ CP} + 0.651 \text{ ash} \quad (4)$$

$$\text{ME (MJ kg}^{-1} \text{ DM)} = 2.20 + 0.136 \text{ GP} + 0.0057 \text{ CP} \quad (5)$$

where GP is expressed in mL per 200 mg DM; CP and ash (% DM) respectively

2.3. Farmers' Preference Ranking of Test Forages

To understand the farmers' preferences, focused group discussions (with semi-structured questions), matrix ranking, and scoring were used. Initially, farmers' selection criteria were developed with a group of three farmers, each in three districts (Adamitulu-Judokombolcha, Halaba and Loka-Abaya) of southern Ethiopia, by asking them to list key attributes of forage plants of their choice. The criteria produced by the three groups were combined. Then, the common criteria for the preference of particular species over the other were used. The criteria included were: (i) palatability and animal preference (feed value), (ii) adaptability (able to grow in poor soil conditions and tolerant to drought), (iii) easy to establish and manage (including easy to harvest), (iv) multipurpose aspect (usefulness as a livestock feed and food), (v) compatibility with other crops, (vi) longevity (perennial nature and providing several harvests). Thereafter, nine farmers—three from each district—ranked forage plants individually (in decreasing importance) according to the predefined criteria. These farmers were involved in on-farm trials of the PhD project. The plants tested were widely grown by smallholders in Ethiopia and the farmers engaged in the study were knowledgeable about the uses and management of the plants. We carried out initial assessment prior to planting the forages.

2.4. Statistical Analysis

Results were analysed using the general linear model procedure of SPSS [27]. Treatments were the seven forage plants. Prior to statistical analysis, gas production data from triplicate syringes for each

sample per incubation run was averaged. Gas and methane production data was subjected to analysis of variance (ANOVA) with the plant sample as the treatment factor (fixed effects) and incubation run as a blocking factor, which was considered as random effects in a randomized complete block design based on the model:

$$Y_{ij} = \mu + \alpha_i + \beta_j + e_{ij} \quad (6)$$

where Y_{ij} = response variable (e.g., CH_4 , GP); μ = the overall mean; α_i = the fixed treatment effect; β_j = effect of incubation run (random) and e_{ij} = the error term. Chemical composition data was analysed in a completely randomized design based on the model:

$$Y_{ij} = \mu + \alpha_i + e_{ij} \quad (7)$$

where Y_{ij} the dependent variable, μ = the overall mean; α_i = the fixed treatment effect and e_{ij} = the error term.

Means of chemical composition data were compared using the least square means procedure. Duncan's multiple range test was employed to compare means of CH_4 production, methane concentration, and total gas production. DM and CH_4 concentration data were log transformed. Means were considered significantly different at $p < 0.05$. Correlation analysis was conducted to quantify the relationship between CH_4 production and chemical composition. All statistical analyses were performed using SPSS statistical software version 25 [27].

2.5. Limitations of the Study

In the present study, the national CH_4 emissions from enteric fermentation were estimated using the IPCC Tier 1 methodology, which calculates CH_4 emissions for each animal category by multiplying the animal population by the average emissions factor associated with the specific animal category. Tier 1 factors are fixed values for each animal category in different regions of the world. Thus, this method of inventory does not account for differences in animals' physiological state, diet characteristics, or management in a given production environment [28]. Therefore, there might be some shortcomings in our national enteric CH_4 emissions data. As the emission factors for the Tier 1 method are not based on country-specific data rather are based on broad assumptions, they may not accurately represent the country's livestock characteristics and may be highly uncertain as a result to +50% [16]. However, except for the Tier 1 approach, most other prediction models require a large quantity of detailed information about animal and feed characteristics [16,29], which is difficult to gather in Ethiopia. Research is also unavailable to derive country-specific emission factors or other estimation parameters.

3. Results and Discussion

3.1. Methane Emission from Enteric Fermentation of Ethiopian Ruminant Livestock

It was estimated that total enteric CH_4 emissions from Ethiopian ruminant livestock in 2011 and 2017 were 50,201 Gg CO_2 -eq. and 56,397.61 Gg CO_2 -eq., respectively. Cattle (dairy and non-dairy) were the largest source of enteric CH_4 production in Ethiopia, contributing to 88% of emissions in 2011 and 87% in 2017. The total CH_4 emissions from enteric fermentation in ruminants increased by 12% in 2017 compared to the base year 2011 with an annual growth rate of nearly 2% (Table 1). The current trends in enteric CH_4 emissions are influenced by the increasing population size of goats, sheep, and non-dairy cattle population. This is caused by increases in the ruminant livestock populations, except dairy cattle. This growth in livestock population in the country is driven by the rapidly increasing demand for livestock products, this demand being driven by population growth, increasing incomes, and urbanization [7,8].

Table 1. Estimated enteric CH₄ emissions from ruminant livestock in Ethiopia, annual growth rate, and temporal variations over the period 2011–2017.

Animal Category	Number of Animals (Head) (1000)		CH ₄ Emissions (CO ₂ -eq.) Gg Per Year ³		AGR (%)
	2011 ¹	2017 ²	2011	2017	
Dairy cattle	7447.24	7155.11	8564.32	8228.38	−0.67
Non-dairy cattle total	45,934.96	52,331.55	35,599.59	40,556.95	2.17
Beef cattle	463.92	477.27	359.54	369.88	0.47
Breeding bull	10,899.32	13,602.14	8446.98	10,541.66	3.69
<1 year (calves)	9617.04	10,738.38	7453.21	8322.24	1.84
1–3 years (heifers and steers)	8228.73	9963.21	6377.27	7721.49	3.19
Other matured cows	16,725.94	17,550.56	12,962.60	13,601.68	0.80
Sheep	25,509.00	30,697.94	3188.63	3837.24	3.09
Goat	22,786.95	30,200.23	2848.37	3775.03	4.69
Total ⁴	101,678.15	120,384.84	50,200.91	56,397.61	1.94

¹ Population data [30]; ² population data [1]; ³ emission values were converted to CO₂ equivalent (CO₂-eq.) using the factor [31] of 25 Gg; ⁴ population data reported are collected in December for each year; AGR: annual growth rate.

There are no recent estimates available on enteric CH₄ production from ruminant livestock with which to compare our data.

Nonetheless, the mean annual emissions growth rates recorded in the current study were slightly lower than the previous decade 2001–2011 for the Africa average (i.e., 2.4% per year) [32] and higher than the global average experienced in the earlier decades. According to the recent emissions report by Tubiello et al. [32], enteric CH₄ emission (from all ruminants) during the period 1961–2010 grew with an average annual growth rate of 0.95%. The mean yearly emissions growth rates currently recorded in Ethiopia calls for mitigation strategies to control the increasing CH₄ emissions. This effort may involve improving the quality of the fodder plants included in the ration of grazing ruminants [11,33]. In the following section, we discuss the nutritive value and CH₄ emission reduction potential of selected forage species.

3.2. Nutritive Value and Mitigation Potential of the Forages

3.2.1. Chemical Composition

The chemical composition of the forages was based on crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL). The forages studied differed significantly ($p < 0.05$) in chemical composition (Table 2). Overall, the CP contents among the forages ranged from 3.26 to 30.68%. *S. sesban* had the highest and maize stover the lowest CP concentration. CP serves as a reliable measure of overall nutritional value. A threshold value for an adequate forage quality of 7% CP has been suggested, below which ruminal fermentation of forages may be limited and protein requirements of animals may not be met [34].

On the other hand, Waghorn and Clark [35] argue that forage CP concentrations must exceed 10% of DM for livestock maintenance requirements and about 19% for high-producing dairy cows or young growing stock. In this study, all test forages, except maize stover, had a higher CP content than the threshold level of 7%. However, the CP content of maize stover, *Crotalaria juncea* and *Lablab purpureus* was still below the critical level suggested by Waghorn and Clark [35]. *Sesbania sesban*, *Moringa stenopetala*, *Leucaena leucocephala*, and *Cajanus cajan* were the forages with the highest CP concentration. The high CP content of *S. sesban*, *M. stenopetala* and *L. leucocephala* in particular, suggest that these species can be used as a supplement for ruminants in the study area where native forages are CP-deficient. The utilization of such CP rich forages, in addition to their direct contribution to nutrient supply, may increase DM intake and increase the digestibility of poor quality feeds [36]. Although the CP content of maize stover is lower than the threshold level, with the expansion of cultivation and the resultant decline in grazing resources, crop residues will likely remain an important component of ruminant feeds in many parts of Ethiopia [37]. We also estimated the amount of maize stover produced in the country (discussed in Section 3.5).

The NDF and ADF contents are other commonly used measures to assess feed quality. An NDF content below 35.5% would be considered good quality, while above 46% would be considered poor [38]. In this study, an NDF value below the threshold was observed in *M. stenopetala*, *S. sesban*, and *L. leucocephala*. These forage species also had the lower concentration of ADF. A low ADF content can be seen as positive for forage quality because the lower ADF level means higher digestion [39]. Overall, the NDF and ADF contents were the lowest in *M. stenopetala* (21.1 and 10.9%, respectively) and highest in maize stover (75.9 and 44.7% respectively). The ADL content differed among forages ($p < 0.05$) with the lowest mean value measured in *M. stenopetala* (2.9%) and the highest in *C. cajan* (13.76%). Higher lignin was observed in *C. cajan*, *C. juncea*, and *L. leucocephala*, which are all legumes. Often, tropical forages are known for their higher lignin contents, a factor which can alter voluntary intake and digestibility of the forage [40] causing higher energy loss and resulting in an increase in CH₄ production per unit of product through a decrease in the efficiency of animal production [41]. Owing to the association with polysaccharide constituents, lignin forms a physical barrier and thus hinders the access of rumen microbes to fermentable cell wall components.

Consequently, the passage rate of feeds through the rumen is slowed down, thus limiting dry matter intake [40,42]. Lignin represents an undigested portion of the forage and is associated with fibre. Therefore, the greater the concentration of lignin in a plant, the lower the digestibility of the forage and the less dry matter an animal can consume [42].

In contrast, there are exceptions where lignin concentration and digestibility are not correlated [42] as seen in the current study where we found negative effects of lignin content on CH₄ production (discussed in Section 3.3). The chemical composition of studied forages is comparable with the range of values reported for similar forages for sub-Saharan Africa [43–45]. The chemical composition of the forages is reported in Table 2.

Table 2. Mean (%) chemical composition of the studied forages.

	DM	Ash	CP	NDF	ADF	ADL
Maize stover	92.19 (2.10)bd	7.90 (0.01)a	3.40 (0.20)	75.90 (0.21)	44.68 (0.11)	6.32 (0.11)
<i>L. purpureus</i>	92.90 (0.10)a	8.04 (0.01)a	15.01 (0.01)	44.04 (0.02)	24.22 (0.10)	8.31 (0.10)
<i>C. juncea</i>	94.11 (0.04)bd	7.60 (0.11)	14.50 (0.02)	53.10 (0.20)	44.02 (0.31)	13.70 (0.01)a
<i>M. stenopetala</i>	89.48 (0.06)	12.50 (0.03)	25.90 (0.13)b	20.74 (0.43)	10.86 (0.04)	2.90 (0.01)
<i>S. sesban</i>	94.92 (0.03)bcd	9.40 (0.05)	30.55 (0.20)	28.97 (0.10)	16.58 (0.24)	5.51 (0.21)
<i>C. cajan</i>	93.08 (0.06)a	6.20 (0.11)	19.69 (0.40)a	54.38 (0.01)	32.45 (0.60)	13.76 (0.44)a
<i>L. leucocephala</i>	95.35 (0.04)cd	11.20 (0.01)	25.60 (0.20)ab	34.00 (0.05)	22.22 (0.10)	10.95 (0.66)

Numbers in brackets are standard deviation. In each column, no or lower case lettering is used to show the significant differences between different types of treatments at $p < 0.05$ level.

3.2.2. Metabolizable Energy (ME) and Organic Matter Digestibility (IVOMD)

The nutritive value of a feed is determined by the concentration of its chemical components along with their rate and extent of digestion [46]. Feeds with high IVOMD are likely to have a high potential to supply the ME required to support animal production [47]. In this study, the calculated IVOMD and ME content varied among the forage species studied, ranging between 68 to 93% and 8.46 to 12.3 MJ kg⁻¹ DM, respectively (Table 3). *Moringa stenopetala* and *L. purpureus* exhibited higher IVOMD and ME content (93, 11.28 and 92.4%, 12.3 MJ kg⁻¹ DM, respectively). The ME values of the feeds were within the ranges of reported values for sub-Saharan Africa [45]. All the studied forages, except *C. cajan*, had OMD values above 70%, which suggests that these forages have high nutritional value for ruminants. Meissner et al. (2000), cited in Bezabih et al. [48] reported that forages having an OMD of 70% or more are considered to be of high quality. In line with this, Evitayani et al. [47] reported that the OMD of forages above 50% is a good indicator of their potential to supply ME.

Table 3. In Vitro Organic Matter Digestibility (IVOMD) and Metabolizable Energy (ME) of test forages.

Forage Type	IVOMD (%)	ME, MJ kg ⁻¹ DM
Maize stover	75.34 (6.60)	10.45 (1.00)a
<i>L. purpureus</i>	92.36 (10.04)a	12.31 (1.50)
<i>C. juncea</i>	82.33 (5.40)	10.85 (0.83)a
<i>M. stenopetala</i>	93.01 (5.80)a	11.28 (0.90)a
<i>S. sesban</i>	87.34 (7.62)b	10.42 (1.20)a
<i>C. cajan</i>	67.90 (4.60)	8.46 (0.73)
<i>L. leucocephala</i>	87.48 (6.90)b	10.58 (1.05)a

Numbers in brackets are standard deviation. In each column no or lower case lettering is used to show the significant differences between different types of treatments at $p < 0.05$ level.

3.2.3. Total Gas (mL), CH₄ Production (mL), CH₄ Concentration (%), and CH₄ Production Reduction Potential of the Studied Forages

Total gas and CH₄ production and the proportion of CH₄ in the total gas produced on the test samples are provided in Table 4.

Table 4. Means of total gas production (GP), CH₄ production and concentration (as a proportion (%) of total GP).

Treatments	GP, mL/0.2 g DM	CH ₄ , mL/0.2 g DM	CH ₄ Concentration (%)
Maize stover	144.06 (37.60)b	44.33 (1.41)a	31.73 (7.30)a
<i>L. purpureus</i>	206.40 (54.12)	33.00 (4.71)b	16.25 (1.20)
<i>C. juncea</i>	155.71 (30.43)ab	35.67 (1.41)b	23.45 (5.50)c
<i>M. stenopetala</i>	169.80 (33)a	40.50 (2.60)a	24.16 (3.17)c
<i>S. sesban</i>	137.20 (43.64)b	40.67 (1.41)a	31.06 (8.80)ab
<i>C. cajan</i>	67.40 (26.73)	32.83 (2.21)b	52.22 (17.60)
<i>L. leucocephala</i>	142.40 (37.6)b	35.17 (1.2)b	25.48 (5.90)bc

Numbers in bracket are standard deviation. In each column no or lower case lettering is used to show the significant differences between different types of treatments at $p < 0.05$ level.

Total gas, CH₄ production and percentage of CH₄ concentration varied significantly ($p < 0.05$) among the studied forages (Table 4). Gas volumes from the incubation of 0.2 g substrate ranged from 67.38 to 206.40 mL after 48 h incubation. The total GP was highest for *L. purpureus* and lowest for *C. cajan*. Maize stover generated the most substantial amount of CH₄ (44.33 mL/0.2 g DM incubated) and *C. cajan* and *L. purpureus* the lowest amount, with 32.83 and 33 mL/0.2 g DM, respectively. The difference observed in CH₄ production among the samples is mainly attributed to differences in the fibre contents (see Section 3.3.). The CH₄ concentration (as a proportion of total GP) of forage samples investigated showed high variability ($p < 0.05$), ranging from 16.25 for *L. purpureus* to 52.22 for *C. cajan*. Methane concentration was significantly lower for *L. purpureus* (16.3%) followed by *C. juncea* (23.5%) and *M. stenopetala* (24%) and was higher for *C. cajan* (52.22) than other species (Table 4). Methane as a proportion of total gas could be used as an indicator to determine the capacity of a plant to suppress CH₄ production in vitro [49,50]. Lower CH₄ to gas percentages indicate that a particular candidate would be better as a rumen modifier for CH₄ reduction than those yielding higher percentages. In the current study, *L. purpureus* had the highest CH₄ reduction potential. *Crotalaria juncea*, *M. stenopetala*, and *L. leucocephala* also showed a consistently lower CH₄ percentage, which makes them promising species to reduce CH₄ production in ruminants in the study area. It is also important to note that these species had relatively higher CP concentrations (Table 2), which make them an ideal source of protein supplement in ruminant feed. Most of the promising forages with high CH₄ reduction potentials were also leguminous, except *M. stenopetala*. Legumes which contain higher CP have been shown to be associated with lower CH₄ production. In vitro studies (see, for example, [26,51]) have shown that a large portion of the variability of CH₄ production in legumes can be associated with the presence of secondary metabolites in some legume species, which can inhibit CH₄ formation [52,53].

3.3. Relationship between Chemical Composition and CH₄ Production

In the current study, among the various chemical constituents, ADL contents of the forages studied had only a significant negative correlation ($r = 0.66$) with CH₄ production (Table 5). Here, CH₄ production consistently decreased as the ADL content increased. A possible explanation for this might be that lignin protects fibres from ruminal degradation and thus reduces methanogenesis [54] most likely due to a reduced nutrient availability for the rumen microbes involved in methanogenesis as reported by Hindrichsen et al. [55]. A negative correlation between ADL and CH₄ release observed in the present study is in close agreement with earlier findings of Singh et al. [56] and Hindrichsen et al. [55]. The weak relationship between CH₄ and ADL content of the forages observed in the present study, however, demands caution. The adverse effects of ADL on CH₄ production observed suggest a positive role of lignin in mitigating CH₄ emissions from ruminant production [39]. Despite this rare observation of positive effects of lignin, nutritionists usually suggest to minimize the lignin content of ruminant diets [42]. In the current study, despite considerable variation in the chemical composition of the forages investigated (Table 2), CH₄ production was not significantly correlated with most chemical parameters (Table 5). The presence of plant secondary metabolites (e.g., condensed tannins and saponins) or starch may be responsible for moderating methanogenesis in the rumen and thus CH₄ production, although, their presence was not examined in the current study. For example, condensed tannins containing forage species are thought to reduce CH₄ production in vitro through direct inhibition of methanogens, as well as indirectly limiting methanogenesis through reduced availability of hydrogen [52,53], but they may also reduce animal performance mostly by reducing feed intake and digestibility [57]. In this regard, more detailed studies defining the type and concentration of plant secondary compounds of some of the tested forages (legumes in particular) and selecting effective ones, which could reduce CH₄ production without negatively effecting protein supply, are needed. Additionally, high starch content favours the production of propionate and reduces ruminal pH, thus inhibiting methanogen growth [58]. The correlations between CH₄ production, CH₄ concentration, and chemical composition of forages are presented in Table 5.

Table 5. Correlations coefficients between CH₄ production, CH₄ concentration and forages chemical composition ($n = 14$).

	DM	Ash	CP	NDF	ADF	ADL
CH ₄ production (mL/0.2 g DM)	−0.32	0.30	−0.20	0.11	0.02	−0.66 *
CH ₄ concentration (%)	0.10	−0.41	0.03	0.27	0.18	0.30

Level of significance: * $p < 0.05$.

3.4. Farmers' Preferences and Ranking of the Studied Forage Species

Moringa stenopetala was found to be a highly preferred species for its palatability and animal preference, easy propagation, adaptability, easy establishment and management, multipurpose nature, and its compatibility with other crops (Table 6). *Moringa stenopetala* constitutes a vital component of the mixed farming systems found in parts of southern Ethiopia. The plant is mainly grown on farm boundaries and in the homestead. This is a fast-growing tree that is tolerant of drought and poor soil conditions and can survive for many years [59]. All these features might have contributed to the farmers' choice of this tree among the studied forage plants. Next to *M. stenopetala*, farmers in the study area had a high preference for *C. juncea* and *L. leucocephala*, both of which showed promising performance in terms of their values to farmers (Table 6). Although *Sesbania sesban* is widely cultivated in the study areas, farmers had shown low level of preference for this multipurpose tree. This could be a consequence of its poor agronomic performance in terms of adaptability, establishment, and biomass production in these areas, in particular in Ziway and Halaba (first author's personal observation and informal discussion with farmers).

Table 6. Farmers' preference and ranking of the forages.

Forages Criterion	Maize Stover ^a	L. purpureus	C. juncea	M. stenopetala	S. sesban	C. cajan	L. leucocephala
Palatability and animal preference	0.04	0.19	0.20	0.24	0.11	0.08	0.14
Adaptability	0.11	0.17	0.25	0.25	0.10	0.00	0.12
Easy to establish and manage	0.08	0.15	0.23	0.22	0.11	0.12	0.10
Multipurpose	0.21	0.08	0.07	0.25	0.11	0.15	0.13
Compatibility with other crops	0.07	0.09	0.22	0.24	0.12	0.14	0.12
Longevity	0.03	0.06	0.09	0.21	0.21	0.18	0.21
Sum of weighted scores ¹	0.55	0.74	1.06	1.40	0.76	0.67	0.81
Rank ^b	7	5	2	1	4	6	3

^a Maize stover was evaluated only with respect to livestock use. ^b 1 = Most preferred; 7 = Least preferred; ¹ Sum of weighted scores was developed to obtain the final ranking of the studied forages and calculated as: weighted sum = sum of [(7 × number of responses for 1st rank + 6 × number of responses for 2nd rank ... + 1 × number of responses for 7th)] divided by (7 × total responses for 1st rank + 6 × total responses for 2nd rank ... + 1 × total responses for 7th rank).

3.5. Production of Crop Residue and the Potential of the Studied Forages to Intensify Ruminant Farming in Ethiopia Sustainably

In Ethiopia, most of the available feed energy and protein supplies for ruminants originate from rangelands and crop residues. Communal or private natural grazing and browsing, cut-and-carry system combined with tethering of animals, are the commonly practiced feeding systems in the country. Crop residues are estimated to cover up to 50% of the feed supply in mixed systems, whereas grassland resources cover up to 90% of livestock feed in pastoral systems [5]. Reports from the highland areas of East Africa show that maize yields, although subject to a general lowering, are likely to increase, providing more human food and animal feed [15]. Concentrates are expensive and seldom used in the country (see, for example, Assaminew and Ashenafi [60]). Above all, with the expansion of cultivation and shrinkage of the traditional grazing areas, crop residues are becoming an increasingly important component of ruminant feeds in many parts of Ethiopia [37,61]. We estimated the amount of crop residue produced from one of the major crops (i.e., maize) produced in the country [62]. Owing to the scarcity of data, dry matter obtainable from natural pastures and other land use categories such as forests was not estimated in this study. Using the recommended conversion factor [63] and based on national crop production data [64], we estimated that nearly 16 million tons of maize stover was produced in 2016/2017 in Ethiopia (Appendix A Table A1). In light of the various uses of maize stover on-farm (fodder, mulch, fuel) in the country, our intention here is to give an indication of dry matter quantity of the stover produced, not the quantity offered to livestock or potentially available to animals. Inadequate feed quality, typified by high NDF and low protein contents, and inadequate amount of feed impede improved animal production in Ethiopia. In the present analysis, maize stover exhibited the lowest CP concentration (3.40%) and a higher concentration of NDF (75.90%) and ADF (44.68%).

Furthermore, maize stover had the lowest emission reduction potential (Table 4) and was the least preferred by the farmers (see Section 3.4). However, given the expected long-term reliance on crop residues, replacing or reducing maize stover use would be difficult, or even impossible. Animals feeding on these resources will, therefore, require additional protein. Some of the forage plants tested here have the potential to provide adequate protein at a minimum cost. To this end, the value of *S. sesban* (CP: 30.55%), *M. stenopetala* (CP: 25.9%), *L. leucocephala* (CP: 25.6%) and *C. cajan* (CP: 19.7%) needs due acknowledged as they have the highest CP concentrations (Table 2). The use of these forage species could clearly help to rectify some of the problems associated with low feed quality and partly address the major problems of long-term sustainability of crop-livestock systems in southern Ethiopia. There is a possibility of integrating these species in farmland along the farm border or around homesteads. This strategy could allow farmers to use their land simultaneously for the cultivation of crop, forage, and trees, where products can have multiple uses [5]. The current promotion of sustainable intensification of crop–livestock systems at the national level [7,65] is a good opportunity for scaling out

these promising forage species in mixed farming systems in Ethiopia, thereby contributing to improved utilization of maize stover, reduced environmental damage, and improved livestock productivity.

4. Conclusions

Total enteric CH₄ emission from ruminant livestock in Ethiopia increased by 12% or \approx 6197 Gg CO₂-eq. in 2017 compared to the year 2011. The analysis leads to the conclusion that CH₄ emissions from ruminant livestock in Ethiopia amounted to an annual growth rate of nearly 2%, which is higher than the global average experienced between 1961 and 2010 (0.95%). As we discussed earlier, promising forage plants with high feeding quality and low CH₄ production potential were identified. Nonetheless, *L. purpureus*, *C. juncea*, *M. stenopetala*, and *L. leucocephala* were found to have such desirable qualities. Overall, with the exception of maize stover, all the forages species evaluated in this study were of high CP concentration. The high CH₄ reduction potential and high levels of CP content of these forages could be used for CH₄ mitigation while simultaneously enhancing protein supply in ruminant's forage diets in southern Ethiopia. We have shown that multipurpose forage species such as *C. juncea*, *M. stenopetala*, and *L. leucocephala* greatly reduced CH₄ emissions, had high CP contents, and were preferred by the farmers', which would provide an exciting pathway for intensifying the mixed farming system in southern Ethiopia. The current promotion of sustainable intensification of crop–livestock systems in Ethiopia is a good opportunity for scaling out these promising forages in the country. Nevertheless, there is a need for screening the species using larger datasets to identify where and how to best promote these multipurpose forage species for wider adoption in the country. We suggest that future research should consider optimum level of inclusion of maize stover with the identified promising forage species through feeding experiment to improve livestock production in southern Ethiopia and beyond.

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Appendix A

Table A1. National estimates of maize stover produced per annum in the 2016/2017 production year in Ethiopia.

Residue	Grain Production (10 ⁶ ton)	Conversion Factor	Estimated Maize Stover Production (10 ⁶ ton) **
Maize *	7.85	2	15.69

* Crop residue production was estimated by multiplying the amount of grain produced with established conversion factor for the crop [63]. ** Does not include stover produced by commercial large-scale farms. Source: CSA report [64].

Annex 1 Equation employed to calculate gas production

$$GP_t = [(SV_t - SV_0) - (BV_t - BV_0) \times 0.2 \text{ g}]/ACW$$

GP_t = volume of gas produced at time “t”

SV_t = syring reading for the sample at time “t”

SV₀ = syring reading for the sample at the beginning of the incubation

BVt = mean of the three replicates blank readings at time “t”.

BVo = mean of the three replicates blank readings at the beginning of the incubation.

ACWs = actual weight of the sample incubated on dry matter basis

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