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Research Article
Chemical Compositions and *in vitro* Methane Production Potentials of Some Agro-industrial By-products and Crop Residues

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Abstract

Background and Objective: Crop production provides a range of agro-industrial by-products and crop residues that have been utilized by ruminants and non-ruminants. However, they are also potential sources of methane emission. Moreover, limited information is available on the methane production profiles of these by-products and crop residues. Thus, this study was conducted to evaluate the chemical, mineral and amino acid compositions and methane production profiles of agro-industrial by-products and crop residues. **Materials and Methods:** Feed samples of agro-industrial by-products and crop residues were collected and processed and ground to pass 1 mm sieve size. Chemical, mineral and amino acid compositions were analyzed using standard procedures. *In vitro* gas and methane production profiles were determined according to established procedures. **Results:** Meat and bone meal (MBM) and fish offal waste (FOW) contained high crude protein (574 and 487 g kg^{-1} DM, respectively). Calcium and phosphorous concentrations in MBM were 67.6 and 36.1 g kg^{-1} DM, respectively. Fat content in FOW was highest followed by MBM. Wheat bran had the highest starch (387 g kg^{-1} DM) and noug seed cake (NSC) the highest iron (4383 g kg^{-1} DM) and manganese (189 g kg^{-1} DM). The NSC contained higher concentrations of arginine, cystein, methionine and histidine than those of wheat bran. Methane production was highest ($p<0.05$) in wheat bran while it was lowest ($p<0.05$) in FOW. **Conclusion:** The FOW and MBM might be used as suitable feed combinations with crop residues to mitigate methane emission from the livestock agriculture.

Key words: Agro-industrial by-products, wheat bran, crop residues, methane production, crop production, fish offal waste, noug seed cake, enteric methane, gas production kinetics

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

In most developing nations, like Ethiopia, livestock have low productivity because they are fed almost entirely on natural pasture and crop residues. However, crop production provides a range of agro-industrial by-products that have been utilized by ruminants and non-ruminants in urban and peri-urban areas. The most common agro-industrial by-products produced and used widely in Ethiopia are noug seed (*Guizotia abyssinica*) oil cake, wheat bran and meat and bone meal[1]. Noug (*Guizotia abyssinica*) is an oilseed crop mainly cultivated in different parts of Ethiopia and India. It constitutes about 50% of the Ethiopian and 3% of Indian oilseed production[2]. Fish offal waste has been also considered as another potential animal feed by-product from freshwater lakes[3,4]. These feed resources have been mainly used in ration formulations for both ruminant and poultry by filling the gap in the feed supply, decrease competition for food between humans and animals, reduce feed cost and contribute to self-sufficiency in nutrients from locally available feed sources. Crop residues also represent the major feed resources in most developing nations. In Ethiopia, straws from teff *(Eragrostis teff)*, wheat, barley and maize stover are the most common crop residues used in livestock feeding[1]. However, they are considered as potential sources of methane emission if fed to livestock alone leading to increased green house gas emissions[5].

Even though feeding animal origin feeds (meat and bone meal) to farm animals is prohibited in most developed nations, such feed ingredients are still playing a major role in the nutrition of livestock in most developing nations[6]. Dumping or burning agro-industrial by-products, particularly those from animal products processing industries, present potential air and water pollution problems in developing nations. However, they can be beneficial in enhancing the nutritional status of different forms of rations and feeds of livestock as these contain various amounts of macro and micro-nutrients that are essential for body growth and productivity[7]. Moreover, these feed resources could be used as potential nutrient supplements to improve the quality of crop residues in the livestock agriculture. Although the nutritive values of agro-industrial by-products and crop residues have been reported by previous scholars, the results were highly variable and inconsistent. A full-fledged data on both macro and trace minerals as well as amino acid profiles for most agro-industrial by-products and crop residues are also scanty[6,8,9]. Moreover, limited data are available in the literature on the methane production profiles of these by-products and crop residues. Thus, the specific objectives of this study were to evaluate the chemical, mineral and amino acid compositions, *in vitro* gas production characteristics and methane production profiles of some tropical agro-industrial by-products and crop residues.

MATERIALS AND METHODS

Feed sample collection and processing: Samples of wheat bran and noug seed (*Guizotia abyssinica*) cake (NSC) were purchased from Flour and Oil Factories, respectively. Meat and bone meal (MBM) sample was purchased from local Abattoir Enterprise. The local concentrate was obtained from Animal Feed Processing Section of Hawassa University. Sample of fish offal waste (FOW) was collected from the lake Hawassa. The FOW included the gut, head, skin, scale, gills and gonads of tilapia (*Oreochromis niloticus*). The waste was then chopped into smaller pieces using a knife and cooked in boiled water for 17 min. After cooling, the cooked offal was gently removed and thinly spread on plastic sheet and sun-dried.

Samples of maize stovers and straws from wheat, barley and teff (*Eragrostis teff*) were collected after grain harvesting. Crop residues were first chopped to reduce the sizes of the feed material at the site of collection and then sun-dried on plastic sheets. All dried samples were then ground to pass 1 mm sieve size and stored in labelled air-tight plastic bags until analysis. The experiment was conducted from June, 2013 to November 2014 at the Institute of Animal Nutrition, University of Hohenheim, Germany.

Chemical analyses: Analyses of proximate nutrients and fiber fractions were performed as outlined by VDLUFA[10] at the Institute of Animal Science, University of Hohenheim, Germany. The samples were analyzed for DM (method 3.1), ash (method 8.1), crude protein (CP, method 4.1.1), petroleum ether extract (EE, method 5.1.1) and crude fiber (CF, method 6.1.1). Neutral detergent fiber (aNDFom) was assayed on organic matter basis after amylase treatment and acid detergent fiber (ADFom) on organic matter basis (methods 6.5.1 and 6.5.2, respectively). Acid detergent lignin (ADL) was analyzed according to method 6.5.3. Starch was analyzed polarimetrically (method 7.2.1) and sugar was determined according to method 7.1.2 and expressed as sucrose equivalents. Minerals were determined according to methods 10 and 11 using an Inductively Coupled Plasma spectrometer (ICP-OES).

Analysis of amino acids was only performed on feed samples of wheat bran and noug seed cake due to their frequent usage in the nutrition of non-ruminant animals such as poultry. Amino acid contents were measured by ion-exchange chromatography using an amino acid analyzer

L8900 (VWR/Hitachi, Darmstadt, Germany). After a performic acid oxidation step, protein was hydrolyzed with 6 M HCl for 24 h at 113°C. The amino acids were separated on a cation exchange resin and detected after post column derivatization with ninhydrin reagent using visible spectrophotometer (VIS) detection at 570 nm (440 nm for proline). All analyses were run in duplicate and were averaged. If deviation between duplicates was below the level specified for each analysis, the analysis was repeated.

In vitro gas production

Gas production protocols: Gas production (GP) was determined according to the procedure of VDLUFA[10] official method (method No. 25.1). About 200 mg of feed sample was weighed and transferred into 100 mL calibrated glass syringes, fitted with white Vaseline lubricated glass-made plungers. Three syringes with only buffered rumen fluid, termed as blanks (rumen fluid without feed sample), three syringes with hay standard and three with concentrate standard with known GP were included along with each run. Six independent runs were performed for each feed material and standards. Moreover, three replicates per run were used for standards (hay and concentrate) and blanks. The standards of hay and concentrate were used for estimation of metabolizable energy (ME) and organic matter digestibility (OMD) as suggested by Menke and Steingass[11] and Menke *et al*.[12]. The GP of samples, blanks and standards was recorded at 2, 4, 6, 8, 12, 24, 32, 48, 72 and 96 h incubation.

Parameter estimation: Estimation of ME and OMD was computed from the corrected 24 h GP as described:

$$ME\ (MJ\ kg^{-1}\ DM) = 1.68+0.1418*GP+0.0073*CP+0.0217*XL- 0.0028\ XA$$

$$OMD\ (\%) = 14.88+0.889*GP+0.0448*CP+0.0651*XA$$

where, GP, CP, XL and XA are 24 h gas production (mL/200 mg DM), crude protein, crude fat and ash (g kg^{-1} DM) of the incubated feed samples, respectively.

Describing the gas production kinetics: The corrected GP recorded between 2 and 96 h of incubation and the kinetics of GP were described by using the exponential equation:

$$y = b*(1^{-e(-c(t\text{-}lag))})$$

which assumed one pool of asymptotic GP (b, mL/200 mg DM) with a constant fractional rate of GP (c, per h) with a lag phase (colonization time, hour) in the onset of GP and parameter "y" is GP at time "t"[13].

Methane production: For CH_4 determination, five separate *in vitro* runs were performed. The quantity of each feed sample to be incubated for 24 h without removing the produced gas in the syringes during the incubation period was calculated based on the previous *in vitro* GP results. After 24 h of incubation, the total gas production was recorded and the incubation liquid was carefully decanted while leaving the gas inside the syringes. The CH_4 content of the total gas in the syringes was then analyzed using an infrared methane analyzer (Pronova Analysentechnik, Berlin, Germany) calibrated with a reference gas (13.0 vol. (%) CH_4, Westfalen AG, Münster; Germany). Syringes were directly connected to the analyzer and about 20 mL of gas was injected for about 20 sec until the displayed CH_4 concentration was constant. The CH_4 produced by each sample was corrected by the amount of CH_4 produced by blank syringes (containing only the rumen fluid) and by the factors of reference hay and concentrate feed which were included in each run.

Statistical analyses: Results of chemical and mineral compositions are expressed as means for duplicate analysis of a bulked sample. To describe the *in vitro* gas production kinetics, data were fitted to non-linear regression model by using GraphPad Prism 5.0 (2007) for Windows (GraphPad Software, Inc. La Jolla, CA., USA). Data on ME, OMD, GP and CH_4 production were analyzed by one-way ANOVA at $p<0.05$ using the GLM procedure of the Statistical Analysis System[14]. Mean comparisons were performed with the Duncan's multiple range tests.

RESULTS

Chemical compositions: The chemical composition of the main agro-industrial by-products and crop residues is presented in Table 1. Both MBM and FOW contained high levels of total ash and CP followed by NSC. The highest fat content was observed in FOW followed by MBM. Noug seed cake had the highest structured carbohydrates (CF, NDF, ADF and ADL) while FOW the lowest. The sugar content was higher in wheat bran than other by-products. Noug seed cake also contained appreciable amounts of sugar.

Table 1: Chemical compositions of some tropical agro-industrial by-products and crop residues (g kg^{-1} DM)

Feed materials	Ash	CP	EE	CF	aNDFom	ADFom	ADL	Sugar	Starch
By-products									
Wheat bran	41.7	163.0	26.90	82.0	309.0	114.0	30.1	49.2	387.0
NSC[a]	127.0	280.0	14.60	245.0	426.0	403.0	157.0	35.8	26.9
MBM	224.0	574.0	163.00	12.3	224.0	79.3	52.1	-	-
FOW	227.0	487.0	245.00	01.6	34.9	21.3	08.1	-	-
Concentrate	98.3	232.0	64.80	78.9	250.0	136.0	47.0	-	324.0
Crop residues									
Maize stover	104.0	74.9	0.87	284.0	586.0	391.0	45.0	ND	ND
Wheat straw	100.0	28.8	3.03	433.0	762.0	576.0	62.8	ND	ND
Teff straw	66.4	32.7	1.65	397.0	761.0	499.0	46.0	ND	ND
Barley straw	126.0	52.9	3.88	395.0	678.0	532.0	65.8	ND	ND

[a]*Guizotia abyssinica*, NSC: Noug seed cake, MBM: Meat and bone meal, FOW: Fish offal waste, CP: Crude protein, EE: Ether extract, CF: Crude fiber, aNDFom: Neutral detergent fiber on organic matter basis after amylase treatment, ADFom: Acid detergent fiber on organic matter basis, ADL: Acid detergent lignin, ND: Not determined

Table 2: Compositions of major and trace minerals in some agro-industrial by-products and crop residues

	Major minerals (g kg^{-1} DM)					Trace minerals (mg kg^{-1} DM)			
Feed materials	Ca	P	Mg	K	Na	Fe	Cu	Mn	Zn
By-products									
Wheat bran	0.85	7.20	2.88	9.78	0.12	158	8.12	92.40	58.6
[a]Noug seed cake	5.46	6.94	5.28	10.50	0.06	4383	19.50	189.00	65.1
Meat and bone meal	67.60	36.10	1.86	5.16	6.29	410	12.00	8.31	63.8
Fish offal waste	63.50	33.20	1.56	8.13	6.42	378	11.30	74.50	63.5
Local concentrate	16.50	14.50	3.09	8.11	1.69	659	8.24	63.60	54.1
Crop residues									
Maize stover	3.07	1.15	2.96	16.70	0.22	632	2.09	49.10	55.0
Wheat straw	1.49	0.81	0.81	19.60	0.38	139	1.69	30.20	12.0
Teff straw	2.18	1.02	1.03	10.90	0.11	110	4.31	31.90	21.9
Barley straw	3.98	0.52	1.37	18.20	0.97	1369	3.76	111.00	34.7

[a]*Guizotia abyssinica*, Ca: Calcium, P: Phosphorous, Mg: Magnesium, K: Potassium, Na: Sodium, Fe: Iron, Cu: Copper, Mn: Manganese, Zn: Zinc

Table 3: Amino acid concentrations in wheat bran and noug seed cake collected from Ethiopian agro-industrial feed processing plants

	Wheat bran		[a]Noug seed cake	
Amino acids	g kg/DM	g/16 g N	g kg/DM	g/16 g N
Arginine	9.50	5.83	23.9	8.54
Histidine	4.80	2.94	7.80	2.79
Isoleucine	4.50	2.76	9.5	3.39
Leucine	10.0	6.13	17.6	6.29
Lysine	5.80	3.56	9.64	3.44
Methionine	2.50	1.53	4.90	1.75
Phenylalanine	6.50	3.99	12.2	4.36
Threonine	5.20	3.19	9.10	3.25
Valine	6.40	3.93	11.7	4.18
Cysteine	3.30	2.02	5.60	2.00
Alanine	7.40	4.54	11.2	4.00
Aspartic acid	10.5	6.44	26.1	9.32
Glutamic acid	34.8	21.3	54.1	19.3
Glycine	7.90	4.85	14.1	5.04
Proline	12.3	7.55	11.2	4.00
Serine	7.50	4.60	13.9	4.96
Tyrosine	4.50	2.76	7.00	2.50

[a]*Guizotia abyssinica*

The highest and lowest ash values were observed in barely and teff straws, respectively (Table 1). The CP content was low in all crop residues. The fat content in crop residues ranged from 0.87-3.88 g kg^{-1} DM. High ADFom and ADL values were observed in wheat and barley straws.

As shown in Table 2, FOW contained 63.5 and 33.2 g kg^{-1} DM Ca and P, respectively, values being comparable with those observed in MBM. Although relatively deficient in Ca, wheat bran contained considerable concentration of P. Noug seed cake had the highest concentration of Fe and Mn. Both wheat bran and NSC were deficient in Na.

Wheat straw had comparatively lower Ca, Mg, Cu and Zn concentrations. The Ca, Fe and Mn values were highest in barely straw. The highest P, Mg and Zn concentrations were observed in maize stover. Teff straw was rich in Cu. As presented in Table 3, the concentrations of essential amino acids arginine, isoleucine, leucine, methionine, phenylalanine and valine were generally higher in NSC than in wheat bran.

Kinetics of *in vitro* gas production and estimated parameters: As presented in Fig. 1, the highest GP was observed in wheat bran followed by local concentrate while FOW and MBM had the lowest gas. Values for the asymptotic GP (parameter b) and rate of GP (parameter c) were highest in wheat bran and local concentrate and differed from ($p<0.05$) the other by-products. The lag time was positive for wheat bran and local concentrate while it was negative for the other feed materials being the lowest in FOW. The highest ME

Table 4: *In vitro* estimates of metabolizable energy (ME, MJ kg^{-1} DM) organic matter digestibility (OMD, %) and gas production kinetics in some tropical agro-industrial by-products and crop residues

	Estimated parameters		Kinetics of *in vitro* gas production		
Feed materials	ME	OMD	b	c	Lag time (h)
By-products					
Wheat bran	12.3^a	81.00^a	324.00^a	0.113	0.77
*Noug seed cake	7.40^c	59.00^c	142.00^b	0.079	-0.23
Meat and bone meal	10.7^b	67.60^b	92.00^b	0.042	-0.83
Fish offal waste	10.8^b	57.00^c	37.80^b	0.034	-13.00
Local concentrate	12.0^a	80.00^a	268.00^a	0.101	0.89
SEM	0.87	5.05	53.70	0.02	2.65
p-value	<0.001	<0.001	<0.001	-	-
Crop residues					
Maize stover	7.73^a	61.30^a	283.00	0.040	-0.19
Wheat straw	6.47^c	52.70^c	266.00	0.037	1.93
Teff straw	6.65^{bc}	51.30^c	311.00	0.030	1.35
Barley straw	6.92^b	57.60^b	234.00	0.047	2.10
SEM	0.28	2.30	16.10	0.003	0.52
p-value	<0.001	<0.001	0.915	-	-

$^{a-c}$Column means with different superscript letters differ significantly at p<0.05. **Guizotia abyssinica*, b: Asymptotic gas production (mL g^{-1} DM), c: Constant fractional rate of gas production (per h) with a lag time (colonization time, h) in the onset of gas production, SEM: Standard error of the mean

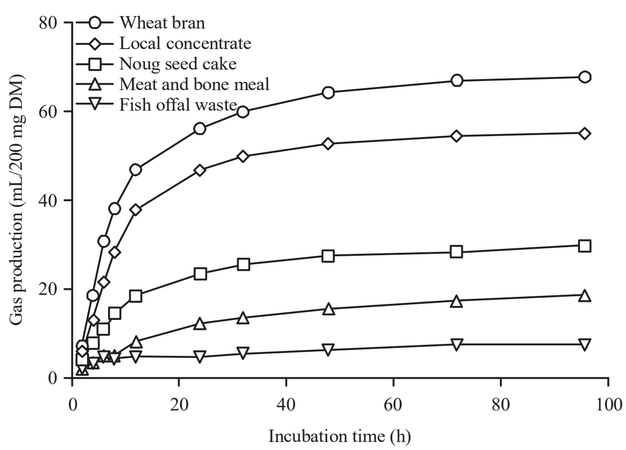

Fig. 1: Patterns of *in vitro* gas production in tropical agro-industrial feed processing by-products and local concentrate

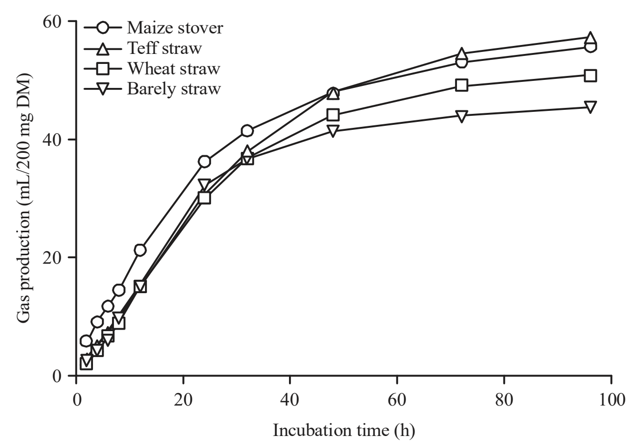

Fig. 2: Pattern of *in vitro* gas production of crop residues of major crops

(12.3 MJ kg^{-1} DM) and OMD (81%) values were observed in wheat bran (Table 4). Fish offal waste had the lowest NGP and OMD values.

As shown in Fig. 2, except in maize stover, other crop residues demonstrated similar GP trends during the first 36 h of incubation after which the pattern for teff straw increased considerably. The highest asymptotic GP (parameter b) and rate of GP (parameter c) were observed in teff and barley straws, respectively. The highest ME and OMD values were obtained from maize stover (Table 4).

Methane production: As shown in Table 5, the lowest CH_4 (1.70 mL g^{-1} DM) was observed in FOW, which differed (p<0.05) from other feed materials. Meat and bone meal (8.60 mL g^{-1} DM) produced lower (p<0.05) CH_4 than the other by-products. However, the percentile CH_4 was higher (p<0.05) in NSC (16.8%) as compared to other feed by-products. The values for absolute and percentile CH_4 as well as NGP for wheat bran were also higher (p<0.05) than those of the other agro-industrial by-products. No differences (p>0.05) were observed between the crop residues in absolute CH_4, GP and percentile CH_4 (Table 5).

DISCUSSION

The nature of the raw materials as well as the processing methods used to produce MBM may result in a highly variable

Table 5: *In vitro* methane and net gas production (mL g^{-1} DM) potentials of tropical agro-industrial by-products and crop residues

Feed materials	CH_4	NGP	CH_4/NGP (%)
By-products			
Wheat bran	46.70[a]	284.00[a]	16.50[a]
*Noug seed cake	19.10[c]	114.00[c]	16.80[a]
Meat and bone meal	8.60[d]	61.50[d]	14.00[b]
Fish offal	1.70[e]	33.80[e]	4.95[c]
Local concentrate	35.20[b]	234.00[b]	14.90[ab]
SEM	8.31	48.70	2.19
p-value	<0.001	<0.001	<0.001
Crop residues			
Maize stover	23.00	185.00	12.50
Wheat straw	20.10	167.00	12.00
Teff straw	20.30	162.00	12.50
Barley straw	24.00	169.00	13.40
SEM	0.98	5.26	0.29
p-value	0.536	0.283	0.952

[a-e]Column means with different superscript letters differ significantly at $p<0.05$
***Guizotia abyssinica*, CH_4: Methane, NGP: Net gas production at 24 h feed sample incubation, SEM: Standard error of the mean

product in terms of chemical composition including the protein quality. Kassahun *et al.*[15] reported 185 and 303 g kg^{-1} DM of CP for wheat bran and NSC, respectively, which are comparable to the current findings. Consistent to the current findings, Hagos and Melaku[16] reported 168 and 317 g kg^{-1} DM of NDF and CP, respectively for wheat bran. Hendriks *et al.*[17] and Adedokun and Adeola[18] reported CP value of 568 and 547 g kg^{-1} DM in MBM, respectively, which are in agreement with the present findings. Dale[19] reported 9.60 and 11.2 MJ kg^{-1} DM ME for MBM from beef and pork, respectively. These values are generally higher than observed in the current study.

The concentration of essential amino acids arginine, cystein and methionine in NSC are higher than those found in soybean oil meal reported by Hossain and Becker[20]. Moreover, NSC contained comparable concentrations of valine, threonine and phenylalanine to that of soybean oil meal. However, NSC is found to be low in lysine, a very important essential amino acid in the nutrition of poultry. Although wheat bran is deficient in lysine, isoleucine and arginine, it contained higher concentrations of cystein and methionine than soybean oil meal observed by Hossain and Becker[20]. Mineral concentrations in crop residues might be influenced by a number of factors such as intensity of agriculture system, agro-climatic environments, stage of growth and harvest, soil type and intensity of fertilizer application[21].

In general, the low CP and high cell wall contents implicated the low nutritive value of crop residues. Singh *et al.*[22] reported slightly lower CP but much higher crude fat contents in maize stover than observed in the current study. Melaku *et al.*[23] reported higher ash, CP and low ADF values for teff straw. The variation might be due to differences in the variety of teff and soil type in which the plant was grown.

The CP content of the investigated dry roughages (except maize stover) was below the ruminant maintenance requirement[24]. Paterson *et al.*[25] suggested that basal feed resources with a CP content of less than 70 g kg^{-1} DM (like teff straw, wheat straw, stover) require protein supplementation. In this regard, fish offal wastes and noug seed oil cakes which had high CP and ME contents could be used as alternative feed supplements to offset limitations on voluntary feed intake of crop residues[25].

The Ca concentrations in maize stover (307 mg kg^{-1} DM) and in barely (398 mg kg^{-1} DM) should fulfill the maintenance requirements of ruminants (270 mg kg^{-1})[24]. Moreover, the Mg concentrations (196 mg kg^{-1}) in maize stover can meet the recommended maintenance requirements of ruminant animals (120-220 mg kg^{-1}). However, the Ca concentrations in teff and wheat straws are unable to meet even the critical levels recommended for ruminants. The P concentrations in all crop residues were low (50 and 115 mg kg^{-1}) and is unable to meet the levels (220 mg kg^{-1}) recommended for ruminants. The low concentrations of many minerals in straws and stovers are probably due to maturity and possible transfer of nutrients to seeds[21].

Consistent with the current results for local concentrate, Getachew *et al.*[26] reported between 6.3 and 7.6 mL/200 mg DM CH_4 production from commercial total mixed rations for lactating dairy cows. The current results for asymptotic GP are only slightly higher (46.8 mL/200 mg DM) than those reported by Getachew *et al.*[26] (40.8 mL/200 mg DM) for lactating cows. In tropical regions, CH_4 emissions from ruminants are mainly caused by poor feed resources that are characterized by high fibrous materials. A suppressing influence of ration with high fat content on CH_4 production has been documented in the literature[27-30]. Recent findings have indicated that fish fat had higher inhibition potential of CH_4 production when combined with concentrate and grass silage than with maize silage[31]. Inthapanya and Preston[27] also reported that CH_4 production was reduced when the CP source was fish meal.

From the current study, FOW contained high levels of fat (about 25% on DM basis) and thus feeding it to ruminants in combination with grass silages or crop residues would be an effective strategy to mitigate CH_4 production without affecting productivity. An appealing finding in the current study might be that the investigated agro-industrial by-products which had a negative lag time produced less CH_4 compared to those with positive lag time that emitted comparatively high methane. Fish offal waste, NSC and MBM had negative lag time and produced the lowest CH_4. Similar trends have been also observed in leaves of multi-purpose trees and forage crops in an *in vitro* study[32,33]. Thus, it appears that those feed materials with reduced lag time might have a direct association with low CH_4 production.

The *in vitro* GP of crop residues increased considerably with incubation time and so did CH_4 production. In agreement with the current observation, Blummel *et al.*[34] reported a highly positively association of CH_4 production with GP. Getachew *et al.*[26] reported a proportional increase of CH_4 with the incubation time suggesting that the slowly digestible fraction of feed (i.e., structural fiber) could be associated with higher CH_4 production.

Energy density of roughages is particularly a primary parameter influencing animal productivity. Except noug seed cake, all other agro-industrial by-products contained adequate energy (ME 2.56-2.94 kcal g^{-1} DM) to meet the maintenance requirement of livestock (ME 2.0 kcal g^{-1} DM)[24]. Nevertheless, all crop residues had lower energy (ME 1.55-1.85 kcal g^{-1} DM) and cannot meet the maintenance requirement of livestock (ME 2.0 kcal g^{-1} DM) recommended for ruminants by NRC[24]. Moreover, the major part of the protein in crop residues is most likely associated with the cell-walls which are known to have low digestibility. Thus, feeding of crop residues in combination with agro-industrial by-products would be a viable feeding strategy to mitigate the enteric methane emission from tropical livestock.

CONCLUSION

Noug seed cake contained high concentrations of arginine, cystein, methionine and histidine. However, it had high structured carbohydrates and thus special care should be taken in its inclusion in broilers' ration. The lowest methane was obtained from fish offal waste followed by meat and bone meal. Thus, these by-products could be combined with crop residues or other forages as CH_4 mitigation strategy while maintaining improved animal productivity under smallholder livestock production system. Animal based experiments are recommended to validate the *in vitro* findings by combining crop residues with those methane reducing by-products.

SIGNIFICANCE STATEMENT

This study discovered the nutritive values and methane production potentials of agro-industrial and crop residues that can be beneficial for mitigating enteric methane emission from the livestock agriculture. This study will help the researchers to uncover the critical areas of promoting those identified methane reducing feed resources as viable option in combination with those poor quality crop residues in ruminant nutrition. Thus, this study signifies the development of a strategy on the effective utilization of by-products and crop residues in livestock nutrition aiming at the reduction of methane emission from the livestock agriculture.

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