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Effect of supplementation of *Moringa oleifera* leaf slurry on performance, rumen metabolites and enteric methane emission of growing Yankasa rams

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Abstract

This study evaluated the anti-methanogenic and nutritional effects of *Moringa oleifera* leaf slurry (MLS) in growing Yankasa rams. Sixteen rams (16.6 ± 3.00 kg) were assigned to four treatments supplying 0, 4, 8, and 12 g MLS kg^{-1} DM intake in a completely randomised design. All animals received the same total mixed ration at 5 % of live weight for 85 days, followed by a 7-day digestibility trial. Enteric methane was measured using a portable IRCD4 infrared gas analyser. MLS supplementation improved ($p < 0.05$) nutrient utilisation and growth performance, and reduced CH_4 per unit of feed intake and CH_4 per unit of NDF digested. Rams that received 8 and 12 g MLS kg^{-1} DM showed higher ($p < 0.05$) volatile fatty acid concentrations than the control. Principal component analysis revealed negative associations between MLS phytochemicals and CH_4/feed intake, CH_4/NDF digestibility, and feed conversion ratio. Overall, MLS inclusion up to 12 g kg^{-1} DM increased feed intake (3.70–8.64 %), weight gain (41.4–44.7 %), feed efficiency (19.6–24.5 %), nutrient utilisation, and volatile fatty acids, while lowering methane emission ratios. Although 4 g MLS kg^{-1} DM appears effective for improving performance, further research should explore alternative feeding strategies and higher MLS levels in Yankasa rams and other ruminants.

Keywords: feed efficiency, greenhouse gas mitigation, methanogenesis, nutrient digestibility, small ruminants

1 Introduction

The livestock industry plays a crucial role in Nigeria's agricultural sector, with sheep significantly contributing to food security and economic development (FMARD, 2020; FAO, 2021). Beyond being a source of meat, milk, and fibre; sheep farming sustains the livelihoods of millions of smallholder farmers. Some of the local breeds have demonstrated a strong adaptive capacity to the tropical ecosystem and potential climate change impacts (Ibrahim *et al.*, 2020). As concerns about greenhouse gas emissions grow, it is essential to explore strategies that reduce methane emissions without compromising animal performance, particularly in smallholder farming systems.

The use of natural feed additives in animal nutrition has gained attention for their potential to enhance animal health and productivity. *Moringa oleifera* leaves, in particular, are highly valued for their rich composition of proteins, vitamins, minerals, and bioactive compounds (Gopalakrishnan *et al.*, 2016; Su & Chen, 2020). Moringa is a versatile multipurpose tree species common in the tropical and subtropical ecosystems of Africa and Asia (Devkota & Bhusal, 2020; Mashamaite *et al.*, 2024). These properties make Moringa an effective dietary supplement for livestock (Nehorai & Shahar, 2018). Extensive research has been conducted on *M. oleifera*'s nutritional benefits, medicinal properties, and its potential to modulate rumen fermentation and mitigate methane emissions (Fuglie, 2001; Anwar *et al.*, 2007; Ibrahim *et al.*, 2022).

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The rumen plays a vital role in the digestion of fibrous plant materials, housing diverse anaerobic microbes - primarily bacteria - that facilitate carbohydrate fermentation. This process results in the production of volatile fatty acids (VFAs), ammonia, and gases such as enteric methane (McSweeney & Palmer, 2001). As methane (CH_4) emissions from ruminants account for around 14 % of global agricultural emissions (IPCC, 2014), the impact of *M. oleifera* supplementation on rumen fermentation and methanogenesis is an area of ongoing research (Makkar & Becker, 2016; Ibrahim *et al*., 2022; El Bilali *et al*., 2024).

Various methods of supplementing ruminant diets with *M. oleifera* or its bioactive ingredients have been explored. For example, Ibrahim *et al*. (2022) examined extracts obtained using aqueous and organic solvents, while other studies have incorporated dried moringa meal derived from leaves, seeds, or pods of the plant into animal diets. Kholif *et al*. (2019) reported that dietary supplementation with *M. oleifera* leaf extract at doses of up to 20 ml per doe improved the fatty acid profile of dairy goat, though its impact on enteric methane production remained unclear. Additionally, Amad & Zentek (2023) found that defatted moringa seed meal supplementation at 2, 4, and 6 g DM per lamb/day had no effect on lamb performance, whereas supplementation of male Barki sheep with moringa seeds at 4 g DM per lamb/day increased body weight. Kekana *et al*. (2019) demonstrated that supplementing dairy cows with 60g/day of moringa leaf meal significantly reduced oxidative stress in milk, while Kekana *et al*. (2022) reported that dietary supplementation with moringa leaf meal at 16.6 g/100 kg body weight had no effect on colostrum yield. The variation in the effects of moringa supplementation can be attributed to factors such as inclusion levels, plant growth stage, extraction methods, and dietary composition (El Bilali *et al*., 2024).

Among resource-limited farmers, using liquid extracts for their bioactive components may not be economically viable, as the residues from the extraction process remain underutilised. Also, *M. oleifera* leaves possess high level of crude protein (20-35 %) and appreciable amount of elemental Sulphur (Anwar, *et al*., 2007; Melesse, 2011; Li *et al*., 2013), which are both capable of influencing enteric methane emission and quality of animal protein. Incorporating dried leaf meal into drinking water presents an alternative method for ensuring precise supplementation. However, there is limited research on the impact of different inclusion levels of moringa leaf slurry on the performance, rumen metabolites, and enteric methane emissions of growing Yankasa rams. Understanding these relationships is essential for developing effective feeding strategies that enhance productivity, while reducing the environmental footprint of livestock farming. The aim of this study was to evaluate the effects of orally administered moringa leaf slurry at different supplementation levels on the performance, rumen fermentation, nutrient digestibility and methane emission of growing Yankasa rams.

2 Materials and methods

2.1 Study site, collection and preparation of moringa leaf slurry

The research was conducted at the Small Ruminant Unit of the Department of Animal Science Teaching and Research Farm, Ahmadu Bello University, Zaria, Nigeria. Fresh and clean *M. oleifera* leaves were harvested at a private farm in Samaru Zaria, and then shed-dried to constant weight for five days, milled using a 1 mm sieve and stored in an air tight polythene sack. The *M. oleifera* leaf slurry (MLS) was prepared by mixing 250 g of dried, milled moringa leaf with 1 L of clean water. Oral doses were calculated for each ram based on its daily DM intake to provide supplementation levels of 4, 8, or 12 g kg^{-1} DM. This corresponded to approximately 16, 32, and 48 ml of slurry, respectively.

2.2 Experimental animals, treatments and design

Sixteen (16) growing Yankasa rams (16.6 ± 3.00 kg) were randomly assigned to four treatment groups and balanced for live body weight. The rams were housed individually, each in a pen equipped with a drinker and a feeding trough. Two weeks before the start of the experiment, all rams received a prophylactic health protocol consisting of oral albendazole (0.25 ml per kg^{-1} live weight) for deworming, intramuscular tylosin (0.50 ml per ram) to reduce the risk of bacterial respiratory infections, and subcutaneous ivermectin (0.50 ml per ram) for control of internal and external parasites. This period also allowed the animals to adapt to the housing and drenching procedures. The control group received clean water as a placebo, while rams in the other three treatment groups were supplemented with moringa leaf slurry at 4, 8 and 12 g kg^{-1} DM intake for 85 days.

2.3 Chemical analyses of moringa leaf and experimental diet

The dry matter (DM), ash, and crude protein of the milled moringa sample and the experimental diet were analysed following AOAC (2000) procedures 934.01 (dry matter), 942.05 (ash) and 968.06 (Kjeldahl crude protein). Acid detergent fibre (ADF), neutral detergent fibre (NDF), and acid detergent lignin were determined using Ankom 200/220 system (Ankom Technology, Fairport, NY, USA) according to Van Soest *et al.* (1991). Ether extract was measured using the Tecator Soxtec (HT6) system (AOAC, 2000). Furthermore, oxalates (Oke, 1966), phytate (Wheeler & Ferrel, 1970), tannins (AOAC, 1975), saponin (Uematsu *et al.*, 2000) and alkaloid (Harborne, 1973) were analysed using standard procedures.

2.4 Experimental diet and feeding of animals

The rams were offered a total mixed ratio composed of soyabean hulls, maize offal, groundnut cake, parboiled rice offal, limestone, bone meal and common salt, as presented in Table 1. Each ram was fed twice daily a total rate of 5 % of its live body weight (as-fed basis), with feed allowance adjusted every 14 days according to changes in body weight. *M. oleifera* leaf slurry was supplemented at 4, 8, or 12 g MLS kg^{-1} of each ram's DM intake. The slurry was administered manually and orally using a 60 ml syringe at 07:30 h before the morning feeding. Daily feed intake for each ram was calculated as the difference between feed offered and feed refusals.

2.5 Rumen gas collection and analysis of enteric methane gas

At the ninth week of the feeding trial, rumen gases were collected and analysed for methane using a portable IRCD4 infrared gas analyser. Rumen gas was collected as described by Wang *et al.* (2016) with slight modification. A 60 ml syringe was used to collect rumen gas at 3 hr post feeding, every three days, for two weeks. Prior each sampling, the actual feed intake of each ram was recorded. For sampling, the needle was inserted into the rumen headspace via the central area of the left paralumbar fossa, which has been swabbed with ethanol. Rumen gas was collected into the 60 ml syringe by pulling the plunger. The syringe outlet was then fitted securely to a pre-calibrated methane detector tube of the IRCD4 analyser (Beijing Shian Technology Instrument Co., Ltd., Beijing, China). The collected gas was injected into the analyser inlet at the rate of 2 ml s^{-1}, and the methane concentration (%) for each ram was recorded.

2.6 Digestibility and nitrogen balance study

The rams were housed in individual metabolic crates for total fecal and urine collection for a 7-day period following 24 hours adjustment period to the condition of the metabolic crates. A 5 % of live weight daily total mixed ration with 60 % of the feed at 07:30 h and the remaining 40 % at 14:00 h was offered to each ram. Daily fecal outputs were weighed, sub sampled and oven dried at 60°C for 48 hours for dry matter determination. This was later bulked and mixed together for chemical composition analysis. Daily urine output was also collected into a plastic container placed under the metabolic crate containing 20 ml of 0.1M H_2SO_4 to prevent nitrogen loss by volatilization. The collected urine was strained through a layer of cheese cloth to remove detached hair fragments and/or other solid contaminants. A 5 % aliquot of total daily urine output was taken from each ram and stored in the refrigerator pending nitrogen determination.

$$\text{Digestibility coefficient of nutrients} = \frac{\text{Nutrient intake (g/d) - Faecal nutrient (g/d)}}{\text{Nutrient intake (g/d)}}$$

Nitrogen balance calculations were also carried out using the following simple relationship:

$$\text{N-balance (g/d)} = \text{Intake N (g/d) - Faecal N (g/d) - Urine N (g/d)}$$

2.7 Collection and analysis of rumen fluid

At the end of the trial (85 days), a sample of rumen fluid was collected from each ram using a clean sampling tube (10 mm diameter, 90 cm length) attached to a vacuum pump, which drew the rumen fluid into a sterile container. The pH of each sample was determined immediately using a handheld pH meter. A 50 mL subsample was strained through cheese cloth into a sterilised sampling bottle containing 10 % (v/v) H_2SO_4 to trap ammonia and preserved for subsequent analysis. Another 2 ml of strained rumen fluid was centrifuged at 15,000 g for 10 min at 4 °C. From the resulting supernatant, 1.5 ml was transferred into a tube containing 0.15 ml of 25 % (w/v) metaphosphoric acid, mixed thoroughly, and stored at −20 °C for subsequent determination of fermentation end-products. Total volatile fatty acids were analysed using Markham micro distillation apparatus (Barnett & Reid, 1956), and rumen NH3, was determined colorimetrically following Weatherburn (1967).

2.8 Data analysis

At the end of the experiment, all data obtained were subjected to statistical analysis using a general linear model procedure in SPSS 25.0 version and treatment means were compared using the Tukey Test. The mathematical model used was as follows:

$$Y_{ij} = \mu + T_i + e_{ij}$$

Where Y_{ij} = observation on the j-th animal in the i-th treatment, μ = overall mean, T_i = effect of the *i*th Moringa treatment (0, 4, 8 and 12 g kg^{-1} DM), e_{ij}= random error. The principal component analysis (PAST 4 software, version 4.11) was used to show the relationship among the phytochemicals in moringa leaf and the performance indices of growing Yankasa rams.

3 Results

3.1 Ingredients and chemical composition of experimental diets

The ingredients and chemical composition of the experimental diets is presented in Table 1. The dietary treatment fed to all the growing Yankasa rams consisted of 11.56 % crude protein, 31.43 % crude fibre, and 50.70 % soluble carbohydrate.

Table 1: *Ingredients and chemical compositions of experimental diets*

Dietary ingredients	*(%)*
Soyabean shell	30.0
Rice offal	26.0
Maize offal	20.0
Groundnut cake	20.0
Bone meal	25.0
Limestone	10.0
Common salt	5.0
Total	100.0
Chemical composition	*(%)*
Dry matter	92.40
Crude protein	11.56
Crude fibre	31.43
Crude ash	5.19
Ether extract	1.12
Nitrogen free extract	50.70
Acid detergent fibre	38.50
Neutral detergent fibre	60.20
Lignin	8.17

3.2 *Chemical and mineral compositions of* Moringa oleifera *leaf*

The chemical and mineral compositions of the experimental diets are presented in Table 2. The *M. oleifera* leaf slurry administered orally to the rams had 284 g kg^{-1} crude protein, 211 g kg^{-1} crude fibre, and 452 g kg^{-1} soluble carbohydrate. The *M. oleifera* leaf contained high amount (mg kg^{-1}) of calcium, potassium, phosphorus, sulphur, and iron; with relatively higher amount of phytate (10.43 mg/100 g) compared to other phytochemicals examined.

3.3 Moringa leaf slurry supplementation on growth performance of Yankasa rams

Supplementation with *M. oleifera* leaf slurry (MLS) improved growth performance of Yankasa rams (Table 3). Although initial body weights were similar across treatments, rams receiving MLS achieved higher final weights and greater total and daily weight gains than the control group. Feed intake increased slightly with supplementation, but the improvement in weight gain was proportionally greater, resulting in markedly lower feed conversion ratios for all supplemented groups. The absence of a clear dose-response pattern suggests that even low-level inclusion (4 g kg^{-1} DM) was sufficient to enhance nutrient utilisation and support better growth.

Table 2: *Chemical and mineral compositions of* Moringa oleifera *leaf*

Proximate	*g kg^{-1}*
Dry matter	937
Crude protein	284
Crude fibre	211
Crude ash	34.0
Ether extract	11.8
Nitrogen free extract	452
Acid detergent fibre	250
Neutral detergent fibre	385
Lignin	36.8
Mineral profile	*mg kg^{-1}*
Calcium	6917
Magnesium	761
Potassium	3500
Phosphorus	5366
Sulphur	5584
Iron	5088
Manganese	91.8
Copper	48.8
Zinc	18.0
Phytochemicals	*mg/100 g*
Alkaloid	4.25
Oxalate	3.28
Phytate	10.40
Saponin	3.75
Tannin	3.29

3.4 Moringa leaf slurry supplementation on nutrient digestibility of growing Yankasa rams

MLS supplementation improved nutrient digestibility in Yankasa rams (Table 4). All supplemented groups showed higher digestible of dry matter, crude protein, fibre fractions, and major nutrients compared with the control. The response was consistent across inclusion levels, indicating that even low level supplementation was sufficient to enhance digestive efficiency and fibre utilisation.

Table 3: *Effect of supplementation levels of moringa leaf slurry on growth performance of growing Yankasa rams*

	moringa leaf slurry (g kg^{-1} DM)				
Parameter	*0*	*4*	*8*	*12*	*SEM*
Initial weight (kg animal^{-1})	16.6	16.8	16.6	16.4	0.87
Final weight (kg animal^{-1})	22.5^b	25.3^a	24.5^a	24.4^a	1.16
Total weight gain (kg animal^{-1})	5.88^b	8.50^a	7.88^a	8.00^a	1.05
Daily weight gain (g animal^{-1} d^{-1})	69.1^b	100.0^a	92.7^a	94.1^a	8.29
Total feed intake (kg animal^{-1})	81.0^b	87.6^a	84.0^{ab}	88.0^a	3.17
Daily feed intake (kg animal^{-1} d^{-1})	0.95^b	1.04^a	0.99^{ab}	1.05^a	0.04
Feed conversion ratio	14.30^a	10.80^b	11.30^b	11.50^b	1.29

Means within a row with different superscripts differ ($p < 0.05$). SEM = standard error of the mean

Table 4: *Effect of supplementation level of moringa leaf slurry on nutrient digestibility of growing Yankasa rams*

	moringa leaf slurry (g kg^{-1} DM)				
Parameter	*0*	*4*	*8*	*12*	*SEM*
Digestible dry matter	71.1^b	78.3^a	75.9^a	77.2^a	2.66
Digestible crude protein	75.7^b	82.2^a	80.4^a	81.4^a	2.19
Digestible crude fibre	67.6^b	74.9^a	73.5^a	74.9^a	0.82
Digestible ether extract	75.7^b	82.7^a	80.7^a	81.3^a	2.36
Digestible crude ash	70.1^b	77.8^a	74.0^{ab}	76.1^a	2.72
Digestible nitrogen free extract	78.7^b	85.4^a	83.6^a	83.5^a	2.27
Neutral detergent fibre	69.6^b	77.4^a	72.8^{ab}	76.7^a	2.61
Acid detergent fibre	65.4^b	73.3^a	71.1^{ab}	74.3^a	3.46
Lignin	46.3^b	50.02^a	48.2^{ab}	51.4^a	1.09

Means within a row with different superscripts differ ($p < 0.05$). SEM = standard error of the mean.

3.5 Moringa leaf slurry supplementation on nitrogen utilisation of growing Yankasa rams

Supplementing MLS on growing Yankasa rams (Table 5) increased nitrogen intake, nitrogen absorbed and nitrogen retained as % of intake ($p < 0.05$) in rams supplemented with 12 g kg^{-1} DM intake of MLS compared to the rams in the control group. The rams that received 4 and 8 g kg^{-1} DM intake had similar ($p > 0.05$) mean values as the control group. Nitrogen retained was higher ($p < 0.05$) in rams supplemented with MLS compared to the rams on the control group. However, there were no effects noted in the faecal and urine nitrogen due to the supplementation of MLS in growing Yankasa rams.

Table 5: *Effect of supplementation levels of moringa leaf slurry on nitrogen utilisation of growing Yankasa rams*

	moringa leaf slurry (g kg^{-1} DM)				
Parameter	*0*	*4*	*8*	*12*	*SEM*
Nitrogen intake (g d^{-1})	18.9^b	19.7^{ab}	19.7^{ab}	21.1^a	0.86
Faecal nitrogen (g d^{-1})	3.33	3.04	4.00	3.37	0.61
Urine nitrogen (g d^{-1})	6.42	6.12	5.67	6.33	1.02
Nitrogen absorb. (g d^{-1})	15.6^b	16.8^{ab}	15.7^{ab}	17.8^a	0.53
Nitrogen retained (g d^{-1})	9.13^b	10.7^a	10.1^a	11.5^a	0.34
N-retained as % intake	49.0^b	53.9^{ab}	51.5^{ab}	55.0^a	2.83

Means within a row with different superscripts differ ($p < 0.05$). SEM = standard error of the mean

3.6 Effect moringa leaf slurry supplementation on rumen methane emission and rumen metabolites of growing Yankasa rams

Table 6 shows the ratios of the methane to feed intake and NDF digestibility for the rams supplemented with MLS were lower (p<0.05) compared to the rams on the control group, with 12 g kg^{-1} DM intake reducing CH_4/feed intake by 17.39 % and CH_4/NDF digestibility by 32.61 %. Also, supplementing growing Yankasa rams with MLS at 8 and 12 g kg^{-1} DM intake had higher (p<0.05) volatile fatty acids compared to the rams on the control group. The rumen pH, NH_3, and total bacteria count showed no difference (p>0.05) in the three levels of MLS supplementation though, there was a marginal increase in the total bacteria count.

Table 6: *Effect of moringa leaf slurry supplementation on methane emission indices and rumen metabolites in Yankasa rams*

	moringa leaf slurry (g kg^{-1} DM)				
Parameter	*0*	*4*	*8*	*12*	*SEM*
Methane indices:					
CH_4 (g kg^{-1} DM)	18.50	19.25	20.75	18.25	2.13
CH_4/feed intake (g kg^{-1} DM)	23.00^a	20.75^b	20.91^b	19.00^b	0.71
CH_4/NDF digest. (g kg^{-1} DM)	29.87^a	24.61^b	25.08^{ab}	20.13^b	2.51
Rumen metabolites:					
pH	7.00	6.80	6.70	6.75	0.18
Rumen-NH_3 (mg dL^{-1})	20.50	22.25	18.50	19.50	3.51
Volatile fatty acids (mmol L^{-1})	107.25^b	112.50^{ab}	165.00^a	167.50^a	28.66
Total bacteria count ($\times 10^6$ cfu mL^{-1})	40.25	50.25	46.25	48.00	10.14

Means within a row with different superscripts differ ($p < 0.05$). SEM = standard error of the mean. CH_4 = methane; NDF = neutral detergent fibre; NH_3 = rumen ammonia.

The principal component analysis (PCA) plot (Fig. 1) represents the relationship between phytochemicals in *M. oleifera* leaf slurry and parameters such as methane emission, rumen metabolites, and performance of growing Yankasa rams. Component 1 represents the principal axis that account for the majority of percentage variance in the dataset. The plot shows how different variables like rumen ammonia (NH_3), volatile fatty acids (VFAs), methane (CH_4), and other performance indicators such as weight gain, feed intake, feed conversion ratio and NDF digestibility are distributed along the two principal components. Some of the variables like feed conversion ratio and CH_4/TFI were positioned in opposite direction to the identified phytochemicals, indicating inverse relationship to the phytochemicals in the MLS, while the pH and absolute CH_4 production were not affected by MLS supplementation. VFAs had a high positive loading on PC1 (Table 7), indicating that it was highly influenced by MLS supplementation, contributing to increased fermentation and energy metabolism. Alkaloids, saponins, tannins, oxalates and phytates in MLS exhibited positive effects on weight gain, feed intake, digestibility, nitrogen retention and VFA production in growing Yankasa rams. This indicated that the higher amount of these phytochemicals in the MLS supplements could probably cause higher weight gain, feed intake, digestibility, nitrogen retention and VFA production in growing Yankasa rams.

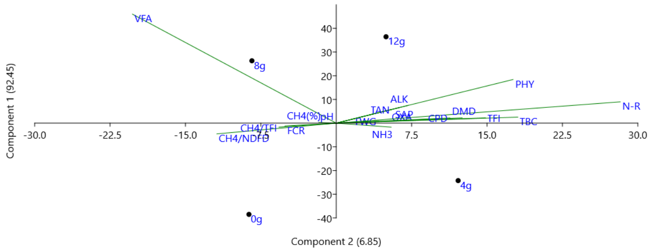

Fig. 1: *Principal component analysis plot 1 vs plot 2 showing the relationship between phytochemicals in* M. oleifera *leaf slurry and methane emission, rumen metabolites and performance of growing Yankasa rams*

4 Discussion

Supplementation of *Moringa oleifera* leaf slurry (MLS) in growing Yankasa rams enhanced feed intake, nutrient digestibility, nitrogen utilisation and growth performance, while simultaneously reducing methane intensity. These improvements are consistent with the nutritional and phytochemical profile of *M. oleifera*. The high crude protein concentration

Table 7: *Principal component loadings relating moringa leaf slurry phytochemicals to methane emission, rumen metabolites, and performance in Yankasa rams*

Parameter	*PC1 × 100*	*PC2 × 100*
Rumen metabolites:		
Volatile fatty acids (VFAs)	89.82	−36.03
Rumen NH_3	−3.24	13.62
Total bacteria count (TBC)	4.80	46.95
pH	0.13	−1.53
Methane indices:		
Methane (CH_4)	0.56	−5.21
CH_4 / NDF digestibility	−8.64	−22.63
CH_4 / total feed intake	−3.11	−15.94
Performance variables:		
Total weight gain (TWG)	1.56	10.96
Total feed intake (TFI)	4.01	39.59
Feed conversion ratio (FCR)	−2.30	−10.15
Nitrogen retained (N-R)	17.12	55.57
Digestibility variables:		
DM digestibility (DMD)	4.22	24.76
CP digestibility (CPD)	4.15	22.34
Phytochemicals:		
Alkaloids (ALK)	14.42	21.92
Oxalates (OXA)	11.13	16.92
Phytates (PHY)	35.39	53.81
Saponins (SAP)	12.72	19.34
Tannins (TAN)	11.16	16.97
% variance explained	92.45	6.85

Loadings were multiplied by 100 for ease of interpretation. CH_4 = methane; CP = crude protein; DM = dry matter; NDF = neutral detergent fibre; NH_3= rumen ammonia.

of the slurry (284 g kg^{-1}) likely supported greater rumen microbial activity and nitrogen availability, contributing to the superior weight gain and feed efficiency observed in supplemented animals. Similar protein driven responses have been reported in small ruminants receiving Moringa-based supplements (Melesse, 2011; Ayssiwede *et al.*, 2011). The elevated levels of calcium, sulphur and phosphorus in the slurry may also have promoted more efficient rumen fermentation, aligning with the shifts in rumen metabolites recorded in this study.

The improved growth performance of the MLS supplemented rams can be attributed to the higher digestibility coefficients and enhanced nitrogen utilisation. These findings mirror those of Amad & Zentek (2023), who observed improved nutrient digestibility and weight gain in male Barki sheep supplemented with Moringa seed meal. Likewise, Kekana *et al.* (2019) reported improved body condition and milk yield in cows receiving Moringa leaf meal, further supporting the capacity of Moringa to enhance nutrient utilisation across ruminant species. The enhanced fibre digestion observed in the present study provides a plausible mechanism for both improved weight gain and reduced methane intensity, as more efficient fibre breakdown typically increases volatile fatty acid (VFA) production while reducing hydrogen availability for methanogenesis.

The anti-methanogenic potential of *M. oleifera* is well documented and is largely attributed to its secondary metabolites, including polyphenols, flavonoids, alkaloids, saponins and tannins (Ibrahim *et al.*, 2022). These compounds can suppress rumen protozoa, redirect hydrogen away from methane formation and modulate microbial populations. Ibrahim *et al.* (2022) demonstrated a 12.97 % reduction in *in vitro* methane production using aqueous methanolic extracts of Moringa leaves, supporting the reductions in methane intensity observed in the present study. The principal component analysis further suggests that the presence of these secondary metabolites may have contributed to the lower methane emission per unit of feed intake and the improved NDF digestibility.

Rumen fermentation characteristics in this study also support a favourable response to MLS supplementation. Total VFA concentrations increased with higher inclusion levels, indicating enhanced carbohydrate fermentation and potentially improved feed efficiency, consistent with the role of VFAs as the primary energy source for ruminants (Morgavi *et al.*, 2020). Rumen pH values (6.70–7.00) remained within the optimal physiological range for fibre degrading microbes (Khan *et al.*, 2020), demonstrating that MLS supplementation up to 12 g kg^{-1}DM intake did not disrupt rumen stability. Rumen ammonia N concentrations (18.50–22.25 mg dL^{-1}) were also within the range required for efficient microbial protein synthesis. Although elevated rumen ammonia can indicate inefficient nitrogen utilisation (Behera *et al.*, 2022), the improved nitrogen balance and digestibility observed in MLS supplemented rams suggest that the additional ammonia was effectively incorporated into microbial protein. The relatively high sulphur content of the slurry may have further supported microbial growth and contributed to methane reduction, consistent with the findings of Li *et al.* (2013), who reported reduced methane emissions in Merino lambs supplemented with dietary sulphur.

Overall, the combined nutritional and phytochemical attributes of *M. oleifera* leaf slurry appear to enhance rumen fermentation, improve nutrient utilisation and mitigate enteric methane emissions in growing Yankasa rams. These results reinforce the potential of Moringa-based supplements as a sustainable strategy for improving small ruminant productivity while reducing environmental impact.

5 Conclusion

The oral supplementation of *Moringa oleifera* leaf slurry at 4–12 g kg^{-1} of individual DM intake improved growth performance, nutrient utilisation and fibre digestibility, while reducing the intensity of enteric methane emissions in growing Yankasa rams. Supplementation at 4 g kg^{-1} DM intake appears particularly promising for enhancing tissue accretion. Further research should explore alternative delivery methods, higher inclusion levels and the applicability of this strategy across other ruminant species to optimise both productivity and methane-mitigation outcomes.

Conflict of interest

The authors declare no conflict of interest to this research work.

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Ethics statement

This study was approved by the institution research ethics and animal welfare committee with the number ABU-CAUC/2024058.

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