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Effect of dietary combinations on productivity and greenhouse gas emissions in lambs

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Abstract

Livestock farming is one of the main sources of global greenhouse gas emissions, particularly methane produced during the digestion process of cattle and sheep, which not only harms the environment but also results in feed energy loss. Therefore, it is essential to understand the patterns and influencing factors of livestock greenhouse gas emissions to improve feed energy efficiency and protect the environment. By feeding different combinations of roughage, production efficiency can be increased and pollution reduced. Different forage compositions lead to varying greenhouse gas emissions in lambs. Understanding the response of productivity and greenhouse gas emissions to dietary combinations, exploring green regulation methods, and focusing on low-carbon emission reduction technologies are crucial for reducing methane pollution, improving feed utilization, ensuring animal health and product safety, and promoting sustainable livestock farming. This study selected 24 healthy lambs of similar weight, randomly divided into four groups of six, and fed different combinations of diets: natural hay, oat hay + natural hay, alfalfa hay + natural hay, and alfalfa hay + oat hay. Feed intake, weight changes, and greenhouse gas emissions were measured during the experiment.

The results showed: (1) Under ad libitum feeding conditions, the dry matter intake of the alfalfa hay + oat hay group and the natural hay group was significantly higher than that of the other two groups ($P<0.05$); the protein intake of the oat hay + natural hay group was significantly lower than that of the other three groups ($P<0.05$). (2) The average daily weight gain of lambs in the alfalfa hay + natural hay group was significantly higher than that in the oat hay + natural hay group ($P<0.05$) . (3) The trend of CH_4 emissions in lambs was similar to that of CO_2, with the natural hay group significantly higher than the other three groups, and the emissions in the alfalfa hay + oat hay group being the lowest; the N_2O emissions in the alfalfa hay + oat hay group were also significantly lower than those in the oat hay + natural hay group. This indicates that feeding natural hay significantly increases the greenhouse gas emissions of lambs .

Introduction

Livestock consumption is projected to increase by 70% by 2025 due to global population growth, urbanization, and rising incomes (FAO 2017). Meeting this growing demand will require significant improvements in animal productivity and feeding efficiency. Efficient animal feeding involves producing economically viable and safe animal products while utilizing natural feed resources effectively an Consequently, animal welfare and health, product quality and safety, and greenhouse gas emissions are critical considerations when developing strategies for precision animal husbandry. Enteric methane emissions from ruminants not only represent an energy loss from their diet (Tseten et al. 2022; van Wyngaard et al. 2018), but also contribute significantly to global warming (Yang et al. 2021). While ruminants emit carbon dioxide (CO_2) through respiration and feed fermentation, this CO_2 originates from biogenic carbon in feed (e.g., plant biomass) and is not classified as a human-induced GHG in national inventories (IPCC, 2021), as it is part of the natural carbon cycle. In contrast, nitrous oxide (N_2O) is closely linked to nitrogen conversion in faeces and urine. Although N_2O emissions are typically lower than CH_4 in ruminants, its high global warming potential (298× CO_2 equivalent) makes it a critical contributor to climate change (IPCC, 2019). Exploring the effects of different forage types on CH_4 and N_2O emissions is essential. Such research can help reduce the environmental footprint of ruminant production while improving energy and nitrogen utilization efficiency, ultimately enhancing animal productivity.

Forage plays a critical role in ruminant feeding systems due to its affordability and abundant dry matter supply. However, its low feeding value makes it insufficient to meet the nutritional requirements of animals for production when used alone (Du et al. 2019). To address this limitation, researchers have explored supplementing natural pasture-based diets with legumes, which are rich in protein and energy (Graham and Vance 2003). Some studies have demonstrated that the use of legumes as a source of roughage in ruminant diets can reduce methane emissions (Alecrim et al. 2024; Quintero-Anzueta et al. 2021). Compared to grass forages, legumes are characterized by lower structural carbohydrate content, faster physical breakdown, and quicker rumen fermentation (Niderkorn et al. 2011). Consequently, feeding legume forages increases the rate of dry matter passage, which is expected to reduce rumen methanogenic activity (Haque 2018a ; grange et al. 2021) Abreu's study showed that a 3:1 grass/legume mixed ration increased organic matter (OM) and crude protein (CP) intake and rumen ammonium nitrogen concentration compared to a diet of only grass (Abreu et al. 2004). In addition, having a higher proportion of NSC in legumes compared to grasses may drive rumen fermentation to produce more propionic acid, thereby reducing hydrogen availability to methanogenic bacteria (Wang et al. 2018). Doran 's study demonstrated that whole gut digestibility of crude and digestible protein was significantly higher in alfalfa : oats = 1:1 diets than in diets with oat hay as a source of roughage (Doran et al. 2007). Moreover, the combination of alfalfa (78%) and oats (22%) in the diet resulted in a reduction of energy loss through lower methane emissions, as compared to a diet with only graminoid forages (McCaughey et al. 1999). However, these studies focused on diets where supplementation of legumes was the only factor considered. Few studies have been conducted to explain the effects of different forage combinations on ruminants. Therefore the aim of this study was to determine the effects of adding alfalfa hay and oat hay to lamb diets on productivity, apparent digestibility of nutrients, and methane production.

Methods

Animals, diets, and study design

The experiment was conducted from June to August 2018 at Baiyinxile Ranch, Xilingol League, Inner Mongolia. The experiment involved 24 Uzhumqin crossbred lambs with an initial weight of 23.56 ± 1.54 kg (mean ± standard deviation). The experiment was conducted in a completely randomised block design with the lambs divided into four groups of six each for a period of two months. The lambs were fed natural hay (N), oat hay + natural hay (NO), alfalfa hay + natural hay (NA) and alfalfa hay + oat hay (AO), and the nutrient composition of the diets is shown in Table 1. The lambs were housed in 1m × 2m pens, dewormed from internal and external parasites and vaccinated before the trial, and pre-fed for 10 days. All lambs were given free access to water and feed samples were collected at feeding time. The daily residue was recorded and used to estimate the feed intake per animal.

Table 1 Diet conventional nutrients (air-dried basis) unit : %

Item	AO	NA	NO	N
Dry Matter （DM）	95.88	97.35	96.65	98.12
Crude Protein （CP）	9.68	10.83	6.49	7.63
Ether Extract （EE）	7.07	7.78	7.03	7.83
Acid Detergent Fiber （ADF）	36.90	47.30	50.10	60.49
Neutral Detergent Fiber （NDF）	60.57	54.66	66.40	60.49
Organic Matter (OM)	91.36	92.43	92.97	94.04

Feed intake and chemical composition

Nutrient intake is determined by the difference between the amount of each ingredient contained in the feed provided and the amount contained in the remaining species. The chemical composition of the diets was carried out at the Grass Public Laboratory, China Agricultural University. The compositions of the feed ingredients were determined by the method of AOAC (1998). The neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed based on the method of Van Soest *et al*. (1991) using an ANKOM fiber analyzer.

Greenhouse gas collection

Methane measurements are made using a combination of a sealed respiratory metabolism chamber, a gas collection tube and a greenhouse gas concentration analyser. The metabolic chamber allows the simultaneous measurement of methane production in two sheep. Each respiratory chamber was equipped with a trough and a water trough, and the test sheep were allowed to feed and drink freely during the test period. The animals were placed in 12 batches (2 animals/batch, 2 animals/group) 3 days before the start of the experimental period and acclimatised for 1 h. The methane and carbon dioxide production as well as faecal and urinary nitrous oxide (NOx) emissions were measured for 1 h after feeding. Emissions of methane, carbon dioxide and nitrous oxide were collected through a gas collection tube for 1 h. The gases were stored in a gas collection bag, and the collected gas samples were analysed using a greenhouse gas concentration analyser (G2308; Picarro; Beijing, China).

Statistical analysis

The experimental data were initially collated using Excel 2021. Statistical analyses were performed using SPSS 27 software and one-way analysis of variance (ANOVA) was used to assess the effect of different feeding combinations on feed intake, nutrient digestibility and GHG emissions. Duncan's multiple range test was used to compare significant differences and the significance level was set at $P < 0.05$.

Results

Feed intake and growth performance

Under ad libitum feeding conditions, the dry matter intake of AO and N was significantly higher than that of the other two groups ($P < 0.05$). The protein intake of NO was significantly lower than that of the other three groups

(P < 0.05) (Fig.1). Additionally, the average daily weight gain of lambs in NA was significantly higher than that of NO (P < 0.05) (Fig.2).

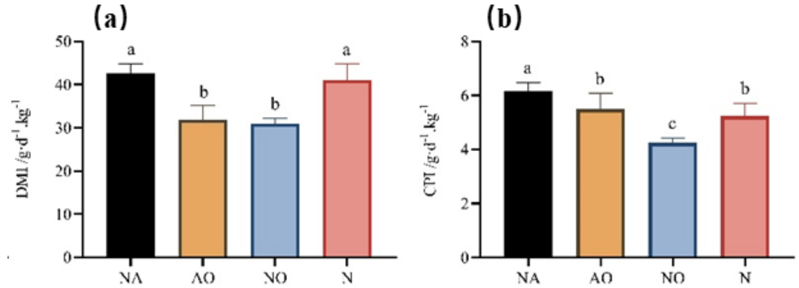

Fig.1 Dry matter and protein intake of different diet groups

Note: NA: alfalfa hay + natural hay; AO: alfalfa hay + natural hay; NO: Oat hay + natural hay; N: Natural hay；a、b、c indicates the difference between dry matter intake and protein intake between diets. Fig.1a shows the dry matter intake of different dietary groups, and Fig.1b shows the protein intake of different dietary groups.

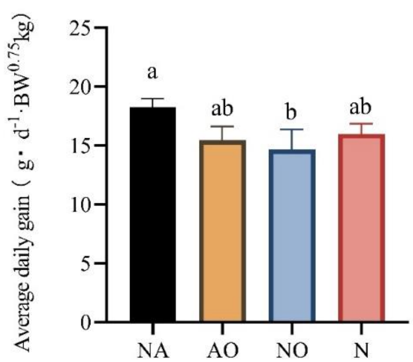

Fig.2 Effect of diet combination on average daily gain of sheep

Note: a、b、c indicates the difference between average daily weight gain of lambs between diets

Apparent digestibility of nutrients
Table 2 shows the effect of different roughage combinations on the apparent digestibility of nutrients in lambs. No significant differences were found between the four roughage combinations in terms of digestibility of dry matter, organic matter and neutral detergent fibre. However, N significantly increased the intake of ADF by lambs (P < 0.05). In addition, ADF digestibility was 26.83% and 19.84% higher with N compared to NA and AO, respectively. In addition, crude protein digestibility was significantly lower (P < 0.01) in N than in the other three treatments.

Table 2 Effects of diet groups on apparent digestibility of nutrients in sheep

Items	NA	AO	NO	N	P-value
Dry matter					
Intake/（g/d）	815.09±33.24	784.16±41.25	707.95±21.64	229.67±20.54	0.277
Feces outpu（g/ d）	356.01±18.66	330.54±20.55	306.83±31.76	331.09±12.00	0.580
Apparent digestibility (%)	22.75±3.63	47.82±1.74	56.71±2.93	56.93±4.09	0.976
Orangic matter					
Intake/（g/d）	753.29±20.71a	716.40±25.41ab	658.19±13.56b	733.30±12.78a	0.047
Feces output（g/ d）	310.11±11.20	277.50±12.66	269.28±15.30	278.65±18.77	0.232
Apparent digestibility (%)	58.29±2.34	61.24±1.27	59.13±1.94	61.43±2.57	0.650
Neutral detergent fiber					
Intake/（g/d）	418.94±11.52	499.89±15.96	447.63±9.22	446.40±19.96	0.412
Feces output（g/ d）	199.48±7.49a	170.66±9.48b	163.39±9.53b	174.0±10.93ab	0.053
Apparent digestibility (%)	58.29±2.34	61.24±1.27	59.13±1.94	61.42±2.57	0.650
Acid detergent fiber					
Intake/（g/d）	277.3±11.39b	262.58±13.23b	255.97±12.66b	340.62±37.42a	0.032
Feces output（g/ d）	117.67±6.97a	104.68±6.70ab	84.86±9.82b	90.25±4.09b	0.015
Apparent digestibility (%)	56.25±3.79bc	59.53±2.44c	66.52±3.73ab	71.34±1.77a	0.007
Crude protein					
Intake/（g/d）	98.21±3.48b	114.33±3.14a	87.18±1.80c	77.04±3.45d	＜0.001
Feces output（g/ d）	43.22±1.06	41.55±2.12	38.96±1.87	40.96±3.07	0.577
Apparent digestibility (%)	61.73±1.77a	57.73±1.58a	55.35±1.73a	45.85±3.97b	＜0.001

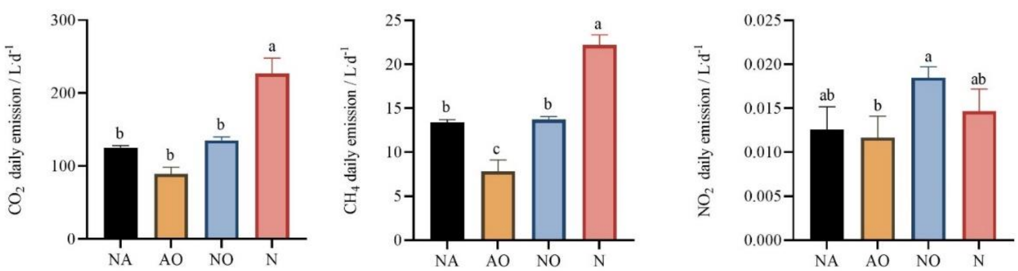

Fig.3 Effects of dietary combination on greenhouse gas emissions of sheep

Greenhouse gas production

The CH_4 emission pattern of lambs was the same as that of CO_2, and N emissions were significantly higher than those of the other three groups. AO emissions were the lowest among the groups. In addition, N_2O emissions were significantly lower for AO than for NO.These results suggest that feeding natural hay significantly increased GHG emissions from lambs ($P < 0.05$) (Fig. 3).

Discussion

Feed type and composition play a crucial role in grazing livestock production systems, significantly influencing nutrient utilization efficiency, animal performance, and greenhouse gas emissions (Schils et al. 2007). Studies have shown that the addition of alfalfa hay significantly improves the nutritional quality of roughage combinations, thereby promoting the daily weight gain of lambs (Wang et al. 2020; Wang et al. 2023). Alfalfa hay, with its high crude protein and low fiber content, provides lambs with sufficient energy and nitrogen to enhance rumen microbial activity and nutrient absorption efficiency (Ishaq et al. 2019). This superior nutritional profile not only improves the nutrient metabolism of lambs but also significantly boosts their growth performance in a shorter time (Ren et al. 2024). In contrast, the oat hay + natural hay group, whilst demonstrating a role in meeting the basic nutritional requirements of lambs, may have limited further improvements in growth performance due to low protein levels (Xiao et al. 2021). In particular, the low nitrogen content of oat hay leads to limited microbial activity in the rumen, which reduces the efficiency of protein catabolism and indirectly affects lamb performance (Kittelmann and Janssen 2011). In addition, although feeding natural hay alone has a higher utilization rate of ADF, its overall protein supply capacity is insufficient. This limitation indicates that relying solely on natural hay as a feed may not meet the growth requirements of lambs, and supplementation with high-protein feeds, such as alfalfa hay, is necessary to compensate for the deficiency (Huang et al. 2021).

The primary greenhouse gases emitted by ruminants include methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), and their emission levels are strongly influenced by feed composition (Broucek 2014).This study further highlights significant differences in greenhouse gas emissions among various feed combinations (Haque 2018b). Methane, the primary greenhouse gas produced during rumen fermentation, is influenced by the type of feed and its fiber content. High-fiber feeds typically result in longer fermentation times in the rumen, promoting the growth of methanogenic microbes (Bharanidharan et al. 2021；Bhatta et al. 2017). In this study, lambs fed natural hay exhibited significantly higher CH_4 emissions compared to other groups. This is attributed to the higher levels of neutral detergent fiber (NDF) and acid detergent fiber (ADF) in natural hay, which provide ample substrates for rumen microbes, thereby increasing methanogenic activity (Wallace et al. 2015). Conversely, the AO group had the lowest CH_4 emissions due to the feed combination's low fiber and high protein content. High-protein feeds pass through the rumen more quickly, reducing fermentation time for methanogens and effectively lowering CH_4 emissions (Pepeta et al. 2024). The CO_2 emissions of the natural hay group were significantly higher than those of other groups, primarily due to increased energy metabolism driven by the high fiber content. Ruminants expend more energy breaking down fiber, and the fermentation process releases greater amounts of carbon-based volatile compounds, further exacerbating CO_2 emissions (Ungerfeld 2020). N_2O emissions from ruminants primarily result from nitrogen transformations in manure and urine, which are influenced by feed nitrogen content and ammonia volatilization (Zhao et al. 2023). This study found that the AO group exhibited significantly lower N_2O emissions compared to the NO group, likely due to the higher protein content of alfalfa hay. This allows for more efficient nitrogen absorption and utilization by the lambs, reducing the accumulation of residual nitrogen in manure.

These findings provide valuable insights for feed management and low-carbon livestock practices in pastoral areas. By reducing fiber content and supplementing with easily digestible, low-fiber feeds (such as alfalfa hay), methane emissions from rumen fermentation can be reduced. Additionally, increasing protein levels and optimizing the inclusion of high-protein feeds in the diet improves nitrogen digestion and absorption efficiency, reducing ammonia volatilization and N_2O emissions. In areas dominated by natural hay, increasing the use of alfalfa and oat hay can enhance livestock productivity while effectively reducing greenhouse gas emissions. Encouraging scientific feed combinations will bring both economic and environmental benefits.

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