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Original Research Article

Evaluation of ginger straw as a forage source for goats: Effects on performance, ruminal fermentation, meat quality and immunity

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ABSTRACT

This study aimed to investigate the effects of ginger straw as a replacement of peanut straw on the growth, meat quality, rumen fermentation, and immunity of goats. In this study, 40 Huanghuai male goats, weighing 30 ± 0.5 kg at six months of age, were selected and randomly divided into four treatments: ginger straw 0% (G0), 5% (G5), 10% (G10) and 20% (G20) replacing peanut straw, with 10 goats in each treatment. Goat dry matter intake (DMI) improved as the proportion of peanut straws replaced with ginger straws increased (linear, $P < 0.001$, quadratic, $P < 0.001$). The highest average daily gain (ADG) and the lowest feed-to-gain ratio (F/G) were observed in G5 goats ($P < 0.001$). The digestibilities of neutral detergent fibre (NDF, $P = 0.031$) and acid detergent fibre (ADF, $P = 0.014$) were higher in the G5 group than in G10 and G20. With increasing ginger straw replacement, the plasma interleukin-10 (IL-10) levels increased (linear, $P = 0.035$, quadratic, $P = 0.041$). The microbial protein (MCP) increased as the proportion of ginger straw increased (linear, $P = 0.034$, quadratic, $P = 0.041$). The butyrate was increased (linear, $P = 0.028$, quadratic, $P = 0.035$) at all levels of ginger straw inclusion into the diet. A linear ($P < 0.001$) increase in the height of the jejunal mucosal villi was observed as the proportion of ginger straw in the diet increased. The tight junction protein 1 (*TJP1*) and claudin-1 mRNA expression in the jejunal mucosa were significantly higher in groups G5, G10, and G20 than in the G0 group ($P < 0.001$). In general, substituting peanut straw with ginger straw in goat diets promoted rumen fermentation and produced more volatile fatty acids and microbial proteins to meet the needs of goats for improved growth performance. Substituting ginger straw for peanut straw improved immunity and the intestinal barrier in goats and did not adversely affect meat quality. Replacing peanut straw with 5% ginger straw in the goat diet resulted in higher NDF digestibility and growth performance. Therefore, the replacement of peanut straw with 5% ginger straw in goat diets is recommended.

1. Introduction

Ginger (*Zingiber officinale Roscoe*) belongs to the family Zingiberaceae and is used not only as a flavoring agent in human food but also as a medicine (An et al., 2016). Ginger is cultivated worldwide. According to the Food and Agriculture Organization statistical database (FAOSTAT), 28 million tonnes of ginger was produced in 2020 (Inthalaeng et al., 2023). China is one of the major producers and exporters of ginger, with an estimated area of more than 2300 square kilometers under ginger cultivation (Li et al., 2019). Ginger contains curcumin, gingerol, flavonoids, and other active antioxidant and antimicrobial substances. Processed ginger products

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(ginger powder, curcumin, etc.) are green and natural feed additives that are widely used in animal production (Abd El-Hack et al., 2020; Kiambom et al., 2021; Pachuau et al., 2021). The addition of curcumin to the diet promotes growth performance of pigs (Shi et al., 2020), broiler chickens (Hafez et al., 2022), and fish (Pirani et al., 2021), and improves the meat quality of broiler chickens (Galli et al., 2020), pigs (Zhang et al., 2020) and ducks (Jin et al., 2021). The addition of ginger extract to piglet diets was found to improve the antioxidant capacity and immunity of piglets (Lee et al., 2013). A recent study in goats suggests that supplementation with curcumin-olive oil nanocomposites improves uteroplacental blood flow, placental growth, and antioxidant capacity in goats (El-Sherbiny et al., 2024). Currently, there are fewer studies on the effect of ginger extract on goat production compared to pigs and chickens.

Usually, only the underground tubers of ginger are utilized. It should be noted that the weight of the stalks and leaves and the tuber part of ginger reaches 1:1, which means that more than 1.4 million tonnes of ginger stems and leaves are discarded in the field every year (Kizhakkayil and Sasikumar, 2011), resulting in environmental pollution and waste (Yu et al., 2021). The annual output of ginger straw in China is nearly 10 million tonnes (Sun et al., 2022), and the efficient use of ginger straw will contribute to environmental protection and agroecological balance. To the best of our knowledge, studies on the use of ginger straw as animal feed are limited, and data on the nutrient content of ginger straw are lacking. Ginger straw is also rich in bioactive substances, but there is a dearth of research on the effects of ginger straw on animal health.

Owing to the high cellulose and lignin contents of ginger straw (neutral detergent fiber, NDF 47% to 52%; acid detergent fiber, ADF 28% to 44%), it is not easily digested by non-ruminants (Sun et al., 2022). For ruminants, however, the rumen is an efficient fiber-degrading fermenter that can efficiently utilize feeds with high cellulose content (Ribeiro et al., 2020; Zhang et al., 2019). Potential cellulolytic bacteria in the rumen include *Fibrobacter succinogenes, Ruminococcus albus, Ruminobacter flavefacien*, *Lactobacillus succinate*, *Trichoderma*, *Actinobacillus*, *Clostridium*, and *Ruminalococcus*, which are cellulose-degrading bacteria that can help ruminants efficiently degrade and digest stover-based feeds (Guder and Krishna, 2019; Zhang et al., 2021c). The addition of plant extracts (e.g., oregano essential oil and curcumin) to diets promotes rumen fermentation (Tian et al., 2023) and increases the proportion of *F. succinogenes, R. albus,* and *R. flavefacien* in the rumen (Zhou et al., 2019; Zhang et al., 2021c), and these bacteria promote fiber degradation. Ginger straw contains active substances such as curcumin and gingerols, which are potentially capable of promoting fiber digestion in ruminants. Peanut straw is a common roughage used in ruminant production in areas where peanuts are widely grown (Khan et al., 2013), and has a crude protein content of approximately 15%. Ginger straw is a roughage with approximately 10% crude protein content (Sun et al., 2022). Therefore, it is possible that ginger straw could be a substitute for peanut straw for ruminant production in areas with extensive ginger cultivation and high yields. The main objective of our study was to evaluate the effects of different proportions of ginger straw replacing peanut straw on growth performance, digestibility, rumen fermentation, meat quality, and intestinal immunity in goats.

2. Materials and methods

2.1. Animal ethics statement

All experimental procedures were approved by the Animal Ethics Committee of the Anhui Science and Technology University (approval no. AK2020088). The sampling procedures were applied according to the Guideline No. 398 of the Ethical Treatment of Experimental Animals (2006) derived from the Ministry of Science and Technology, China.

2.2. Ginger straw and peanut straw

After ginger was harvested in October 2020 from Tongling City, Anhui Province, ginger straw was collected using a combine harvester, dried quickly in a dryer, and crushed (2-3 cm) in a pulverizer, and sieved through a 60-mesh sieve. Peanut straw was purchased from Henan Zhongyuan Grass Co. and crushed to a length of 2 to 3 cm.

2.3. Animals and diets

In this study, 40 HuangHuai male goats, weighing 30 ± 0.5 kg at six months of age, were selected and randomly divided into four treatments: ginger straw 0% (G0), ginger straw 5% (G5), ginger straw 10% (G10) and ginger straw 20% (G20) replacing peanut straw, with 10 goats in each group. The feeding trial lasted for 60 d after 10 d of adaptation. Diets were formulated according to the NRC (2007). Throughout the trial period, the goats were fed a total mixed ration (TMR) diet. Goats were fed daily at 08:00 and 17:00 during the experimental period with free access to feed and water. The nutrient contents of the peanut and ginger straw are listed in Table 1. The dietary energy and protein levels were consistent across all the treatments. The ingredient and chemical composition of the experimental diets are shown in Table 2.

2.4. Feed and fecal samples collection

Approximately 500 g of peanut and ginger straw were collected, crushed, sieved through a 40-mesh sieve, and stored for analysis. During the experimental period, 500 g of feed was collected weekly, dried immediately at 65 °C, and crushed through a 40-mesh sieve. All collected feed samples were mixed and stored for analysis. The duration of the digestibility trial was 12 d, including 7 d of adaption and 5 d of total collection of feces. Six goats per treatment were selected for feces collection from 40 to 45 d of the experimental period; wool and impurities were removed from the feces, and 5% of the total daily weight of the feces was collected. Ten milliliters 10% sulfuric acid was added per 100 g of feces and stored at −20 °C for further analyses.

2.5. Feed and fecal samples chemical analyses

Feed and fecal samples were analyzed for dry matter (DM; method 930.15), crude protein (CP; method 2001.11), ether extract (EE; method 920.39), crude ash (Ash; method 942.05), neutral detergent fiber (NDF; method 2002.04), and acid detergent fiber (ADF; method 973.18) following the procedures of AOAC (2005). Calcium and phosphorus (P) in feed samples were analyzed using

Table 1
Nutrient composition of peanut vine and ginger straw (% of air-dry basis).

Item	Peanut straw	Ginger straw
DM	88.31	88.43
CP	14.46	11.64
EE	2.03	1.15
NDF	44.68	53.58
ADF	28.20	41.39
Ash	15.13	16.42
Lignin	10.63	8.11

DM = dry matter; CP = crude protein; EE = ether extract; NDF = neutral detergent fiber; ADF = acid detergent fiber.

Table 2
Diet composition and nutritional levels of the four treatments (% of DM).

Item	Diet[1]			
	G0	G5	G10	G20
Ingredients				
Corn	19.50	19.50	19.50	19.50
Soybean meal	7.00	7.00	7.00	7.00
Whole corn silage	30.00	30.00	30.00	30.00
Peanut straw	30.00	25.00	20.00	10.00
Ginger straw	0.00	5.00	10.00	20.00
Wheat bran	12.00	12.00	12.00	12.00
Premix[2]	0.50	0.50	0.50	0.50
Salt	1.00	1.00	1.00	1.00
Total	100.00	100.00	100.00	100.00
Nutrient levels				
NDF	32.85	33.29	33.74	34.63
ADF	18.98	19.64	20.26	21.62
Ash	11.30	11.28	10.94	11.04
CP	14.03	13.89	13.74	13.46
EE	2.66	2.62	2.58	2.49
ME[3], MJ/kg	10.44	10.51	10.57	10.71

DM = dry matter; CP = crude protein; EE = ether extract; NDF = neutral detergent fiber; ADF = acid detergent fiber.
[1] G0: 30 % peanut straw +0 % ginger straw; G5: 25 % peanut straw +5 % ginger straw; g; G10: 20 % peanut straw +10 % ginger straw; G20: 10 % peanut straw +20 % ginger straw.
[2] The premix provided the following per kilogram of diet: vitamin A 200,000 IU, vitamin D_3 35,000 IU, vitamin E 800 mg, vitamin K_3 5 mg, vitamin B_1 10 mg, vitamin B_2 20 mg, vitamin B_3 40 mg, vitamin B_5 100 mg, vitamin B_9 2.5 mg, choline chloride 400 mg, Fe 100 mg, Zn 80 mg, Cu 190 mg, Mn 30 mg, I 150 mg, Se 4 mg, calcium hydrophosphate 15 g, NaCl 5 g, Lys 1.5 g, Met 1.5 g.
[3] Metabolizable energy was based on calculated values (NRC, 2007).

inductively coupled plasma mass spectroscopy (AOAC, 2005; method 985.01).

2.6. Determination of secondary components of ginger and ginger straw

Ginger and ginger straw were collected for drying at a mild temperature (about 35-40 °C) and 50 g of the dried samples were kept for determination of secondary components. The extraction of phenolic compounds and curcumin from dried ginger samples was carried out using the phenolic extraction protocol (Johnson et al., 2019). Approximately 0.5 g of ginger and ginger straw powder samples were suspended in 7 mL of 90% aqueous methanol solution and vortexed for 60 min. The sample was then centrifuged at 1000 × *g* for 10 min and the supernatant was collected. The extraction process was repeated with 7 mL of 90% methanol and vortexed for 20 min to extract the remaining polar compounds. The supernatant was combined to a volume of 15 mL. Extracts were stored in a refrigerator (4 °C) until analysis. The extracts were subsequently analyzed by HPLC (Daian Elite Analytical Instrument Ltd., Dalian, China).

2.7. Feed intake and growth performance

The feeds offered and refused were recorded daily throughout the trial to calculate the average daily feed intake. Initial body weights were recorded before the start of the trial and before feeding on the 50th day of the trial to calculate the average daily weight gain.

2.8. Slaughter performance and meat quality

At the end of the experiment, goats were slaughtered to determine carcass traits and meat quality (n = 10). Carcass traits included the following: dressing percentage (%) = (slaughter weight/live weight) × 100, and carcass weight, which is the weight after slaughter and removing the head, hoof, tail, and viscera, and retaining the oil and kidney. The loin eye area (cm^2) was recorded on the cut surface of M. Longissimus dorsi (LD) at the interface of the 12th and 13th rib, on both sides of the carcass (Sen et al., 2004). The GR value (the depth of muscle and fat tissue from the surface of the carcass to the lateral surface of the 12th rib 110 mm from the midline) was directly measured using a GR knife.

The pH of the meat samples was measured at 45 min and 24 h after slaughter using a digital pH meter (S220 K, Mettler Toledo). Different areas were selected for each meat sample and measured in triplicates. After slaughter, the meat color (Lightness, Redness, and Yellowness) was measured using a reflectance spectrophotometer (CR-410, Konica Minolta Sensing, Osaka, Japan). The weighed meat sample was placed in a pot, cooked to a temperature of 70 °C, then removed and cooled for 30 min before weighing to determine the cooked meat rate. The cooked meat rate, shear force, and water loss rate were measured according to the previous report (M Wang et al., 2021).

2.9. Ruminal fermentation

Rumen content (50 mL) was collected before feeding on the morning of the 35th day. The rumen pH (S220 K, Mettler Toledo) was immediately measured, and the average of four measurements was calculated. The filtered rumen fluid (5 mL) was stored at −20 °C until analysis of volatile fatty acids (VFA), ammonia nitrogen (NH_3—N), and microbial protein (MCP). Rumen fluid VFA, NH_3—N, and MCP levels were examined as described in our previous study (Lv et al., 2023). Rumen VFA concentration was analyzed using a GC522 gas chromatograph (Wufeng Instruments, Shanghai, China). To determine the rumen VFA concentration, 1 mL of rumen fluid was mixed with 0.3 mL of metaphosphoric acid (25%, w/v) and allowed to stand for 30 min, then the mixture was centrifuged at 15,000 × *g* for 10 min at 4 °C, and the supernatant was taken to determine the concentration of VFA. Rumen fluid ammonia nitrogen (NH_3—N) concentration was determined by a phenol-sodium hypochlorite colorimetric method after the liquid was thawed at 4 °C. Microbial proteins were analyzed according to the method described previously (Makkar et al., 1982).

2.10. Collection and analysis of blood samples

Blood was collected from the goats (n = 10) by jugular vein puncture on d 50 of the trial, and approximately 8 mL of blood was collected in vacuum blood collection tubes containing EDTA (BD Vacutainer, Belliver Industrial Estate, Plymouth, UK). After that, all blood samples were kept on the ice and taken to the laboratory for plasma separation through centrifuging at 3000 × *g* at 4 °C for 20 min. The supernatants were collected and aliquoted into four 1.5 mL microcentrifuge tubes and stored at −20 °C for analysis. Plasma total superoxide dismutase (T-SOD), total antioxidant capacity, and malondialdehyde (MDA) concentrations were determined according to the manufacturer's instructions (Nanjing Jiancheng Bioengineering Institute, China). The IgG concentration in the plasma was determined using a goat-specific ELISA kit (CUSABIO, Wuhan, China). The concentrations of interleukin-2 (IL-2), interleukin-6 (IL-6), interleukin-10 (IL-10), interferon-gamma (IFN-γ), Immunoglobulin (Ig) G, IgA and IgM were analyzed using a sandwich ELISA technology kit (Jiangsu Meimian, China).

2.11. Jejunum and ileum morphology

After slaughtering, 2 cm intestinal segments were cut from the jejunum and ileum, rinsed gently with phosphate buffered saline (PBS), and fixed with 4% paraformaldehyde for preservation. Goat jejunum and ileum sections fixed with 4% paraformaldehyde were removed, embedded in paraffin, sliced (thickness 5 μm), and

stained with hematoxylin-eosin (HE). The villus height (VH) and crypt depth (CD) were measured using a microscope (Motic BA210, Xiamen, China), and the ratio of villus height to crypt depth ratio (V/C) was calculated. Each section was measured ten times, and the mean value was used for statistical analysis.

2.12. The mRNA expression of immunity-related genes in jejunum and ileum

Immediately after slaughter, the jejunum and mid-ileum were rinsed clean with PBS, and samples of the jejunum and ileum mucosa (approximately 2 g) were placed in sterile sampling bags and stored at −80 °C for analysis. Total RNA was extracted from the intestinal mucosa, cDNA was synthesized, and the detection of gene mRNA expression levels was determined using the previously described method (Lv et al., 2022). RNAiso Plus (TaKaRa, Dalian, China; Code No. 9108/9109) was used to extract total RNA from collected epithelial samples under the manufacturer's instructions. After removing the genomic DNA using DNase I digestion (Thermo Scientific, Waltham, MA, USA), the concentration and purity of total RNA were determined using NanoDrop 2000 (Thermo Scientific, Waltham, USA). Next, utilizing the Evo M-MLV RT Kit (AG11706, Changsha, China) in a 20 μL system, 1 μg of total RNA was reverse transcribed to cDNA under the manufacturer's instructions. Real-time quantitative PCR was carried out using the SYBR Premix Ex Taq II (Takara, Dalian, China) on an ABI-7900HT qPCR system (Applied Biosystems, Foster City, CA, USA). The primers used in this study are listed in Table 3.

2.13. Statistical analysis

Statistical analysis was performed using the PROC MIXED of SAS (version 9.1, SAS Institute Inc., Cary, NC) with the diet as the main effect:

$$Yij = \mu + Ji + eij,$$

where *Yij* is the dependent variable, μ is the overall mean, *Ji* is the fixed effect of treatment (i = 0, 5%, 10%, and 20% ginger straw replacing peanut straw), and *eij* is the random residual error. Tukey's test was used to compare differences among the four treatments. Orthogonal polynomial comparisons were performed to analyze the linear and quadratic effects of ginger straw addition levels. Statistical significance was set at $P < 0.05$. The correlation among intestinal mucosal barrier gene, butyrate, and total volatile fatty acids (TVFA) was assessed using Pearson's correlation test ggplot2 R package (v3.4.4).

3. Results

3.1. Secondary components of ginger straw

As shown in Table 4, ginger contained 57.83 mg/kg of 6-gingerol, 9.69 mg/kg of 8-gingerol, 1.87 mg/kg of 10-gingerol, and 23.66 mg/kg of curcumin. Similarly, ginger straw contained 1.78 mg/kg of 6-gingerol, 0.54 mg/kg of 8-Gingerol, 0.03 mg/kg of 10-gingerol and 2.71 mg/kg of curcumin. Gingerol content in ginger was much higher than in ginger straw.

3.2. Growth performance, slaughter performance, and meat quality

There were linear ($P < 0.05$) and quadratic ($P < 0.05$) effects of ginger straw on DMI, ADG, and the F/G ratio in goats (Table 5). Among the four treatments, goats in G5 had the highest ADG and lowest F/G ($P < 0.05$).

The slaughter performance and meat quality of goats are presented in Table 6. There were no treatment effects on BWS, HCW, DP, LM, GR, pH 45 min, pH 24 h, lightness, redness, yellowness, water loss rate, and cooked meat rate ($P > 0.05$). Linear ($P = 0.023$) and quadratic ($P = 0.041$) effects were observed for the shear force when peanut straw was replaced with ginger straw. Among the four treatments, G0 exhibited the lowest shear force ($P < 0.05$).

3.3. Nutrient apparent digestibility and rumen fermentation

As shown in Table 7, replacing peanut straw with ginger straw had no significant effect on the apparent digestibility of DM, CP, or EE in goats ($P > 0.05$) (Table 7). As the proportion of ginger straw replacing peanut straw increased, there was a linear decrease ($P < 0.05$) in the apparent digestibility of NDF and ADF. The apparent digestibility of NDF and ADF in goats was significantly higher in G5 than in G10 and G20 ($P < 0.05$).

These data suggest that replacing peanut straw with ginger straw improves goat growth performance but reduces digestibility. Rumen fermentation parameters were further examined to inves-

Table 4
Determination of secondary components of ginger and ginger straw (mg/kg dry weight).

Item	Ginger	Ginger straw
6-Gingerol	57.83	1.78
8-Gingerol	9.69	0.54
10-Gingerol	1.87	0.03
Curcumin	23.66	2.71

Table 3
Primers used in the present study.

Gene name	Primer	Sequence (5′-3′)	Size, bp	References
TJP1	Forward	ACCACACTGTGATCCTAAAACCT	77	Lv et al. (2022)
	Reverse	CACAGTTTGCGCCAACAAGA		
Occludin	Forward	ATCGGAGTTTCAGGTGAATGGG	97	Lv et al. (2022)
	Reverse	TCCGCCTGAAGAAGCAGAAAG		
Claudin-1	Forward	CAGGCCTTCTCGTGGTTAGG	93	Lv et al. (2022)
	Reverse	ATGGAACAGGGTGCCAACAA		
Mucin-2	Forward	GGACTCGCACTCATGTGGAA	158	Lv et al. (2022)
	Reverse	CCAAACTCCACGGGACTGAA		
Claudin-4	Forward	CCGCCACGAAACAACAAG	129	Wang et al. (2021)
	Reverse	GGGAGAAACAAAGACGAAAGGA		
β-Actin	Forward	CTTCCAGCCTTCCTTCCTG	111	Lv et al. (2022)
	Reverse	ACCGTGTTGGCGTAAAGGT		

TJP1 = tight junction protein 1.

Table 5
Effect of replacing peanut straw with ginger straw at different ratios on the growth performance of goats ($n = 10$).

Item	Diet[1]				SEM	*P*-value		
	G0	G5	G10	G20		Treat	Linear	Quadratic
DMI, g/d	834.6^{c}	852.2^{b}	879.3^{a}	827.4^{d}	5.74	<0.001	<0.001	<0.001
ADG, g/d	127.0^{b}	143.2^{a}	125.4^{b}	129.6^{b}	7.52	<0.001	<0.001	0.007
F/G	6.58^{b}	5.97^{c}	7.03^{a}	7.16^{a}	0.09	<0.001	<0.001	0.003

DMI = dry matter intake; ADG = average daily weight gain; F/G = feed: gain ratio.
Means with different superscripts within the same row differ significantly ($P < 0.05$).
[1] G0: 30% peanut straw +0% ginger straw; G5: 25% peanut straw +5% ginger straw; g; G10: 20% peanut straw +10% ginger straw; G20: 10% peanut straw +20% ginger straw.

tigate the reasons for improved growth performance in goats. The replacement of peanut straw with ginger straw had no significant effect on rumen fluid pH, acetate, propionate, valerate, isobutyrate, isovalerate, or A/P in goats ($P > 0.05$) (Table 8). Linear ($P = 0.007$) and quadratic ($P = 0.103$) effects were observed for NH_3–N when peanut straw was replaced with ginger straw. The MCP exhibited linear ($P = 0.034$) and quadratic ($P = 0.041$) effects as the proportion of ginger straw increased. The butyrate was increased (linear, $P = 0.028$, quadratic, $P = 0.035$) by incorporating ginger straw into the diet. The TVFA exhibited linear ($P = 0.043$) and quadratic ($P = 0.042$) effects as the proportion of ginger straw increased. The highest concentration of TVFA was found in the rumen fluid of goats in G5 ($P < 0.05$).

3.4. Plasma antioxidant, immunocompetence, and intestinal immunity

Plasma antioxidant properties, immunocompetence, intestinal tissue morphology, and mRNA expression of immune-barrier-related genes were examined to explore whether ginger straw replacement with peanut straw was beneficial to goat health. Replacement of peanut straw with ginger straw had no significant effect on plasma glutathione peroxidase (GSH-Px), MDA, IgA, IgG, IL-2, and IL-6 in goats ($P > 0.05$) (Table 9). Linear ($P = 0.036$) and quadratic ($P = 0.048$) effects were observed in goat plasma total antioxidant capacity (T-AOC) by replacing peanut straw with ginger straw. Goat plasma T-SOD increased linearly ($P = 0.041$) with the increasing percentage of ginger straw. With increasing ginger straw, the plasma IL-10 increased linearly ($P = 0.035$) and quadratically ($P = 0.041$). Plasma IFN-γ exhibited linear ($P = 0.021$) and quadratic ($P = 0.039$) decreases as the proportion of ginger straw increased.

Table 7
Effect of replacing peanut straw with ginger straw at different ratios (%) on the nutrient apparent digestibility of goats ($n = 10$).

Item	Diet[1]				SEM	*P*-value		
	G0	G5	G10	G20		Treat	Linear	Quadratic
DM	70.31	71.01	70.48	70.93	1.361	0.314	0.471	0.536
CP	63.25	62.89	63.37	63.88	2.372	0.105	0.216	0.334
EE	58.53	59.16	59.31	58.47	1.337	0.301	0.229	0.308
NDF	56.17^{a}	55.43^{ab}	53.88^{b}	49.92^{c}	3.059	0.031	0.012	0.250
ADF	44.28^{a}	43.01^{b}	42.59^{bc}	41.13^{c}	2.090	0.014	0.008	0.306

DM = dry matter; CP = crude protein; EE = ether extract; NDF = neutral detergent fiber; ADF = acid detergent fiber.
Means with different superscripts within the same row differ significantly ($P < 0.05$).
[1] G0: 30% peanut straw +0% ginger straw; G5: 25% peanut straw +5% ginger straw; g; G10: 20% peanut straw +10% ginger straw; G20: 10% peanut straw +20% ginger straw.

No significant effect of ginger straw was observed on jejunal mucosal crypt depth and V/C values in goats ($P > 0.05$) (Fig. 1). An increase in the height of the jejunal mucosal villi was observed as the proportion of ginger straw in the diet increased (linear, $P < 0.001$). Substituting ginger straw for peanut straw had no significant effect on the mRNA expressions of occludin, mucin-2 and claudin-4 in the jejunal mucosa ($P > 0.05$). Linear ($P < 0.001$) and quadratic ($P < 0.001$) effects were observed in the mRNA expressions of *TJP1* and claudin-1 by replacing peanut straw with ginger straw. The *TJP1* and claudin-1 mRNA expressions in the jejunal mucosa were significantly higher in the G5, G10, and G20 groups than in the G0 group ($P < 0.05$).

No significant effect of including ginger straw in the diets was observed on ileal mucosal villus height, crypt depth, and V/C values in goats ($P > 0.05$) (Fig. 2). Linear ($P < 0.001$) and quadratic ($P < 0.001$) effects were observed in the mRNA expression of *TJP1* by replacing peanut straw with ginger straw.

Figure 3 shows the heat map analysis of the correlation of intestinal immune barrier genes with rumen butyric acid and TVFA. There was a significant positive correlation between the expression of *TJP1* in jejunal mucosa and butyric acid content in rumen fluid ($P < 0.01$). There was a significant positive correlation ($P < 0.01$) between the expression of *TJP1* and claudin-1 in the ileal mucosa and the butyric acid content in the rumen fluid.

Table 6
Effect of replacing peanut straw with ginger straw at different ratios on the slaughter performance and meat quality of goats ($n = 10$).

Item	Diet[1]				SEM	*P*-value		
	G0	G5	G10	G20		Treat	Linear	Quadratic
BWS, kg	18.63	19.10	18.95	18.87	1.642	0.114	0.215	0.377
HCW, kg	9.09	9.29	9.28	9.17	0.670	0.501	0.674	0.415
DP, %	48.81	48.66	49.01	48.57	1.094	0.219	0.809	0.413
LM, cm^2	12.14	12.32	12.41	12.08	0.633	0.771	0.642	0.598
GR value, mm	19.18	19.21	19.57	19.36	2.412	0.441	0.367	0.609
$pH_{45\ min}$	6.74	6.72	6.78.	6.71	0.048	0.903	0.658	0.214
$pH_{24\ h}$	5.74	5.76	5.79	5.76	0.089	0.235	0.281	0.203
Lightness (L*)	31.94	32.03	32.14	32.20	2.144	0.715	0.205	0.742
Redness (a*)	13.14	13.25	13.67	13.19	1.156	0.304	0.644	0.361
Yellowness (b*)	2.36	2.31	2.29	2.34	0.078	0.757	0.280	0.776
Water loss rate, %	19.58	19.69	20.03	19.67	2.791	0.924	0.636	0.196
Shear force, kg	2.79^{a}	2.61^{c}	2.65^{b}	2.63^{bc}	0.063	0.037	0.023	0.041
Cooked meat rate, %	53.69	54.12	54.03	53.97	2.611	0.655	0.770	0.306

BWS = body weight before slaughter; HCW = hot carcass weight; DP = dressing percentage; LM = loin muscle area.
Means with different superscripts within the same row differ significantly ($P < 0.05$).
[1] G0: 30% peanut straw +0% ginger straw; G5: 25% peanut straw +5% ginger straw; g; G10: 20% peanut straw +10% ginger straw; G20: 10% peanut straw +20% ginger straw.

Table 8
Effect of replacing peanut straw with ginger straw at different ratios on the rumen fermentation of goats ($n = 10$).

Item	Diet[1]				SEM	*P*-value		
	G0	G5	G10	G20		Treat	Linear	Quadratic
pH	6.11	6.09	6.15	6.10	0.055	0.811	0.427	0.560
NH_3–N, mg/dL	9.96^{a}	9.51^{b}	9.24^{c}	9.33^{c}	0.341	0.014	0.007	0.103
MCP, mg/mL	6.97^{b}	6.96^{b}	7.16^{ab}	8.41^{a}	0.856	0.016	0.034	0.041
Acetate, mmol/L	36.42	38.49	36.16	37.15	3.637	0.447	0.463	0.248
Propionate, mmol/L	17.56	18.13	17.96	18.17	1.276	0.202	0.806	0.714
Butyrate, mmol/L	4.18^{c}	5.57^{b}	5.88^{a}	5.89^{ab}	0.342	0.011	0.028	0.035
Valerate, mmol/L	0.96	0.93	0.94	0.89	0.122	0.183	0.524	0.948
Isobutyrate, mmol/L	0.79	0.77	0.81	0.76	0.143	0.689	0.404	0.489
Isovalerate, mmol/L	0.64	0.66	0.68	0.65	0.118	0.231	0.306	0.327
TVFA, mmol/L	60.50^{c}	64.65^{a}	62.46^{b}	63.51^{ab}	4.685	0.022	0.043	0.042
A/P	2.07	2.12	2.01	2.04	0.130	0.565	0.494	0.239

MCP = microbial protein; TVFA = total volatile fatty acids; A/P = acetic acid to propionic acid ratio.
Means with different superscripts within the same row differ significantly ($P < 0.05$).
[1] G0: 30% peanut straw +0% ginger straw; G5: 25% peanut straw +5% ginger straw; g; G10: 20% peanut straw +10% ginger straw; G20: 10% peanut straw +20% ginger straw.

Table 9
Effect of replacing peanut straw with ginger straw at different ratios on the plasma antioxidant capacity and immunity of goats ($n = 10$).

Item	Diet[1]				SEM	*P*-value		
	G0	G5	G10	G20		Treat	Linear	Quadratic
T-AOC, U/mL	26.15^{c}	28.97^{a}	28.55^{b}	28.49^{b}	2.693	0.012	0.036	0.048
T-SOD, U/mL	72.47^{c}	80.16^{b}	81.31^{a}	82.18^{a}	3.971	0.020	0.041	0.052
GSH-Px, μmol/L	27.78	28.14	27.96	28.03	1.992	0.561	0.521	0.353
MDA, μmol/L	9.36	9.29	9.39	9.23	0.075	0.623	0.705	0.883
IgA, mg/mL	14.51	14.56	14.32	14.29	1.032	0.215	0.668	0.481
IgM, mg/mL	34.18^{c}	36.19^{b}	37.52^{a}	37.93^{a}	1.171	0.034	0.011	0.126
IgG, mg/mL	28.99	28.61	29.05	28.67	2.911	0.848	0.443	0.790
IL-2, ng/L	730.14	721.45	740.98	738.17	13.572	0.597	0.943	0.214
IL-6, ng/L	374.58	359.01	364.19	375.18	25.339	0.535	0.865	0.471
IL-10, ng/L	871.63^{c}	885.17^{b}	889.64^{b}	900.38^{a}	21.083	0.017	0.035	0.041
IFN-γ, ng/L	495.47^{a}	468.35^{c}	463.19^{c}	462.33^{b}	19.577	0.044	0.021	0.039

T-AOC = total antioxidant capacity; T-SOD = total superoxide dismutase; GSH-Px = glutathione peroxidase; MDA = malondialdehyde; IgG = immunoglobulin G; IgA = immunoglobulin A; IgM = immunoglobulin M; IL-2 = interleukin-2; IL-6 = interleukin-6; IL-10 = interleukin-10; IFN-γ = interferon-gamma.
Means with different superscripts within the same row differ significantly ($P < 0.05$).
[1] G0: 30% peanut straw +0% ginger straw; G5: 25% peanut straw +5% ginger straw; g; G10: 20% peanut straw +10% ginger straw; G20: 10% peanut straw +20% ginger straw.

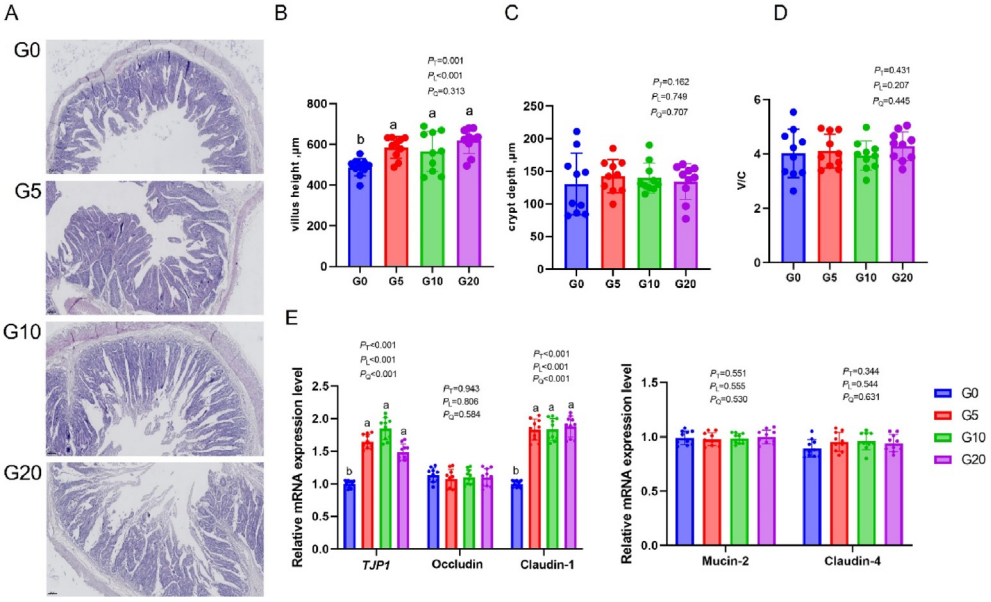

Fig. 1. Substituting ginger straw for peanut straw improves nutrient absorption and immunity in the jejunum of goats. (A) Jejunal tissue morphology between different treatments. All photos were taken at magnification 20×. (B) Height of jejunal villus. (C) Jejunal crypt depth. (D) Jejunal V/C value. (E) The mRNA expression of immunity-related genes in the jejunal mucosa. G0: 30% peanut straw +0% ginger straw; G5: 25% peanut straw +5% ginger straw; g; G10: 20% peanut straw +10 % ginger straw; G20: 10% peanut straw +20% ginger straw. Different lowercase letters (a-b) in the bar chart indicates significant differences between groups. $P < 0.05$ was considered statistically significant. $n = 9$. T = treatment; L = linear; Q = quadratic; *TJP1* = tight junction protein 1; V/C = villus height to crypt depth ratio.

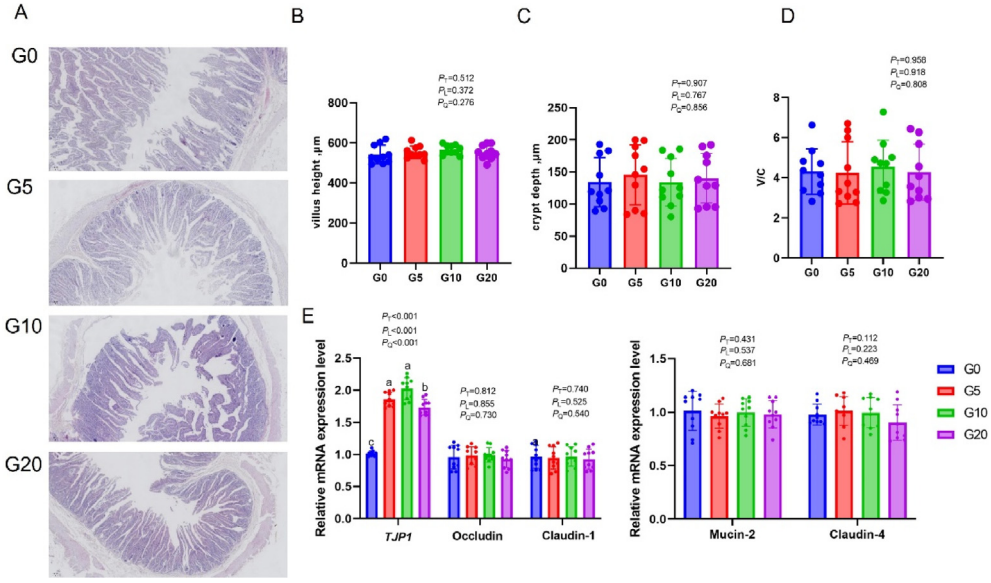

Fig. 2. Substituting ginger straw for peanut straw improves immunity in the ileum of goats. (A) Ileal tissue morphology between different treatments. All photos were taken at magnification 20×. (B) Height of ileal villus. (C) Jejunal crypt depth. (D) Ileal villus height to crypt depth ratio (V/C). (E) The mRNA expression of immunity-related genes in the ileal mucosa. G0: 30% peanut straw +0% ginger straw; G5: 25% peanut straw +5% ginger straw; g; G10: 20% peanut straw +10% ginger straw; G20: 10% peanut straw +20% ginger straw. Different lowercase letters (a-b) in the bar chart indicates significant differences between groups. $P < 0.05$ was considered statistically significant. $n = 9$. T = treatment; L = linear; Q = quadratic; *TJP1* = tight junction protein 1.

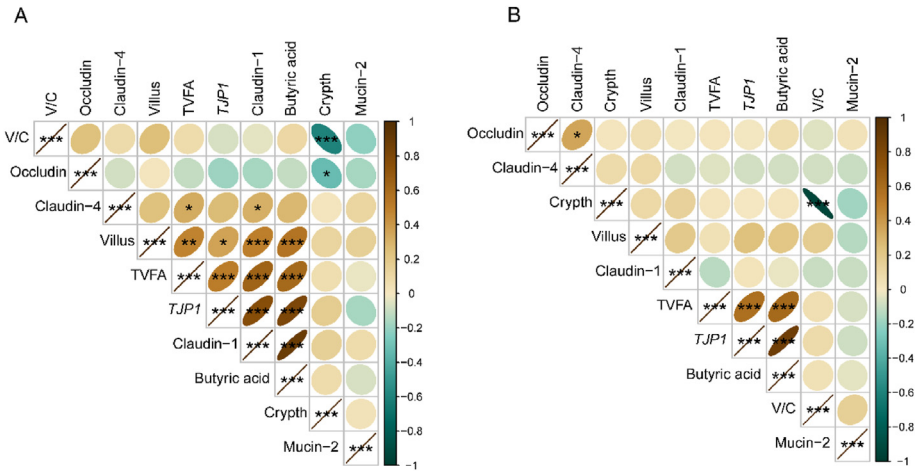

Fig. 3. Heatmap analysis of the correlation between intestinal immune barrier genes and rumen butyric acid and TVFA. (A) Jejunal mucosa; (B) ileum mucosa. The depth of color represents the value of *r*, and the size of the elliptical shape represents the value of *p*. Brown represents positive correlation and cyan represents negative correlation. The flatter the ellipse, the smaller the *p* value. The values of *r* and *p* are listed in the supplementary file. The vertical axis represents the correlation coefficient. *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$. TVFA = total volatile fatty acids; *TJP1* = tight junction protein 1; V/C = villus height to crypt depth ratio.

4. Discussion

The replacement of peanut straw with ginger straw increased DMI and ADG in goats throughout the experiment, indicating that ginger straw had no adverse effects on goats. In this study, ginger straw improved goat feed intake which is possibly due to the active substances in ginger straw (Zhang et al., 2021b) that were measured in this study, although gingerol and curcumin contents were very low. Modern pharmacological research has shown that 6-gingerol and ginger phenol stimulate gastrointestinal tract nerve endings, cause intestinal peristalsis, and improve appetite (Sadakane et al., 2011). In addition, the present study found that the addition of ginger straw to the diet reduced the digestibility of NDF and ADF and increased the rate of gastrointestinal tract emptying in goats (Oba and Allen, 1999), which may also explain the increase in feed intake in goats. The DMI of goats gradually increased with increasing proportions of ginger straw in the diet, but the ADG of goats was highest when peanut straw was replaced with 5 % ginger straw but decreased at higher inclusion rates. The present study found that the digestibility of NDF and ADF in goats decreased significantly as the proportion of ginger straw in the diet increased. This may be due to the higher NDF and ADF contents of ginger straw compared to those of peanut straw (Table 1). The high NDF and ADF content in ginger straw accelerates gastrointestinal emptying and decreases NDF and ADF digestibility (Lv et al., 2023). Similar findings have been reported when fattening rabbits were fed fermented ginger straw, which improved growth performance but reduced NDF and ADF digestibility (Sun et al., 2022).

Replacing peanut straw with ginger straw caused a decrease in digestibility, but improved growth performance. The rumen fermentation parameters were examined to further explain the increase in growth performance. The rumen fluid pH reflects microbial fermentation and rumen health. The pH of rumen fluid is generally in the range of 5.5 to 6.2 (Cherdthong et al., 2010), and the pH of rumen fluid from all the goats in our study was within the normal range, indicating that ginger straw did not adversely affect rumen fermentation. The data in this study showed that replacing ginger straw with peanut straw reduced NH_3–N content and increased MCP concentration in goat rumen fluid. Proteins in the diet are degraded in the rumen to produce NH_3–N, and microorganisms in the rumen can use NH_3–N to synthesize MCP for the body (Broderick and Muck, 2009). The NH_3–N content in the rumen decreased, whereas the MCP content increased, indicating an increase in the ammonia-nitrogen conversion rate. The appropriate NH_3–N content (6.3–27.5 mg/dL) can ensure the growth and reproduction of microorganisms in the rumen, which is conducive to the synthesis of MCP (Wang et al., 2013). The rumen fluid NH_3–N content of all goats in the present study exceeded 6.3 mg/dL, which could meet the synthesis demand of rumen MCP. Replacing peanut straw with ginger straw improved the efficiency of NH_3–N utilization in goats and promoted MCP synthesis. Feeding fermented ginger straw satisfied the NH_3–N requirements of rabbit gut microbes (Sun et al., 2022), similar to the results in our study. The results in this study showed that substituting ginger straw for peanut straw increased the butyrate concentration in the rumen of goats. Volatile fatty acids (VFA) are the primary source of energy for ruminants (70%–80%) (Mertens, 1987), and the data in this study suggest that replacing peanut straw with 5% ginger straw increases the concentration of TVFA in the rumen of goats, thus providing more energy for goats to meet their higher growth performance requirements.

Consumers are concerned about the meat quality when they buy meat. The evaluation indices of goat meat quality include pH, meat color, water loss rate, shear force, and cooked meat rate (van Wyk et al., 2022). The results in this study showed that the value at pH 24 h was lower than that at pH 45min. Typically, the pH of live animal muscles remains neutral. After slaughter, the lactic acid produced by glycolysis cannot be removed through blood circulation and accumulates locally in large quantities, resulting in a decrease in post–slaughter muscle pH (McGeehin et al., 2001). A muscle pH of 5.8 or less at 24 h after slaughter is considered desirable in goats (Teixeira et al., 2005). In our study, the pH of all treated goat muscles slaughtered for 24 h was less than 5.8, within the normal range. The data in this study shows that dietary treatments did not affect meat pH or water loss rate. Goat meat color was evaluated using L*, a*, and b* values, with L* values representing brightness, a* values representing redness, and b* values representing yellowness. The lower the L* value, the higher the a* value, and the lower the b* value, the better the meat color is considered (Jung et al., 2003). The substitution of peanut straw with ginger straw had no significant effect on the meat color of goats. This implies that replacing peanut straw with ginger straw has no adverse effects on the meat quality of goats. Surprisingly, ginger straw in the diet reduced muscle shear force, suggesting that ginger straw improves goat muscle tenderness.

Ginger has been shown to improve immunity, and our data suggest that ginger straw promotes goat growth. However, it remains unclear whether ginger straw improves immunocompetence in goats. Therefore, the antioxidant capacity of plasma, immunity, and immune barrier function of the intestine were analyzed. Indicators of antioxidant capacity include T-AOC, T-SOD, GSH-Px, and MDA. T-AOC reflects the combined effects of all antioxidants present in an organism. T-SOD and GSH-Px are antioxidant enzymes that scavenge free radicals from the body and prevent oxidative damage. MDA is a lipid peroxidation product that causes cellular dysfunction (Ghiselli et al., 2000). If the body's antioxidant capacity is impaired, plasma T-AOC, T-SOD, and GSH-Px levels decrease, and MDA levels increase (Chao et al., 2019). In the present study, replacing peanut straw with ginger straw increased the T-AOC and T-SOD activity in goat plasma. Increased plasma antioxidant capacity in goats may be associated with the curcumin in ginger straw. Curcumin has been found to improve the antioxidant status of laying hens (Nawab et al., 2019). IgA, IgG, and IgM are immunoglobulins in animals, of which IgG and IgM can resist bacterial and viral invasion and IgA is immunoreactive to IgG and IgM (Long et al., 2021). The replacement of peanut straw with ginger straw increased the plasma IgM content in goats, implying that ginger straw could improve the immunity of goats. Studies in broilers have shown that ginger powder can increase IgA and IgG levels and improve immunity (Herawati et al., 2022). The ginger extract also increases IgM levels in the serum of non-smokers (Mahassni and Bukhari, 2019). IL-10 induces B cell proliferation, differentiation, and antibody production, and promotes cellular and humoral immunity (Couper et al., 2008). IFN-γ belongs to pro-inflammatory cytokines and can lead to intestinal epithelial cell barrier dysfunction (Sanjabi et al., 2009). The data indicates that ginger straw increased the concentration of IL-10 and decreased the concentration of IFN-γ in goat plasma. The replacement of peanut straw with ginger straw improves the antioxidant and immune capacity of goats, which may be related to the presence of active substances, such as curcumin and gingerols, in ginger straw (Kahkhaie et al., 2019; Lu et al., 2011; Smith et al., 2018). Using a correlation analysis heatmap, there was a significant positive correlation between rumen fluid butyrate content and the intestinal mucosal barrier genes, *TJP1* and claudin-1. Butyrate is believed to enhance the immune capacity of the body (Zhang et al., 2021a); therefore, the increase in the immune capacity of goats fed ginger straw may be related to an increase in the concentration of butyric acid in the rumen.

As the main digestive and absorptive organ of animals, the development and health of the intestinal tract are related to growth performance. Generally, the greater the height of the villi in the intestine, the better the ability to absorb nutrients (Casas et al., 2020). In the present study, substituting ginger straw with peanut straw increased the villus height in the jejunum. The improved growth performance of ginger straw-fed goats was also associated with better absorption capacity of the jejunum. The intestinal mechanical barrier mainly consists of intestinal epithelial cells and connectivity complexes, which form the structural basis for maintaining the permeability of epithelial cells and their barrier functions (Sanz and De Palma, 2009). Because ginger and its extracts have been shown to modulate intestinal health, the mRNA expression of genes associated with the intestinal mucosal barrier was examined (*TJP1*, occludin and claudins). Tight junctions between intestinal epithelial cells comprise tight junction proteins (TJPs) claudins and occludin (Peltonen et al., 2007). Occludin is mainly involved in maintaining the stability of tight junctions (Morrow et al., 2010). The present study revealed that ginger straw enhanced the expression of *TJP1* and claudin-1 in jejunal mucosa, and increased the expression of *TJP1* in ileal mucosa (Fig. 4). This implies that replacing peanut straw with ginger straw may improve intestinal mucosal barrier integrity in goats.

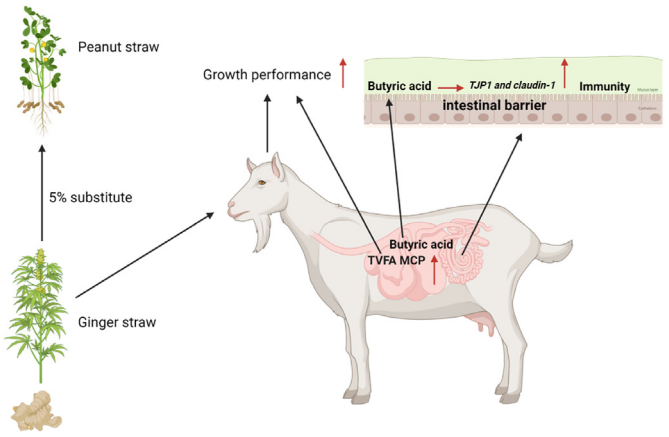

Fig. 4. Replacement of peanut straw by 5% ginger straw in goat diets increased DMI, promoted VFA and MCP production in the rumen, and improved growth performance. Replacing peanut straw with ginger straw increased butyric acid content in the rumen, and butyric acid promotes the expression of intestinal *TJP1* and claudin-1 and improves intestinal immunity. DMI = dry matter intake; VFA = volatile fatty acids; MCP = microbial protein; *TJP1* = tight junction protein 1.

5. Conclusion

Substituting ginger straw for peanut straw in goat diets promotes rumen fermentation to produce more fatty acids and microbial proteins to meet the needs of goats and improve their growth performance. Substituting ginger straw for peanut straw improved immunity and the intestinal barrier in goats and did not adversely affect meat quality. Replacing peanut straw with 5% ginger straw in the goat diet resulted in higher NDF digestibility and growth performance. Therefore, the replacement of peanut straw with 5% ginger straw in goat diets is recommended.

Credit Author Statement

Xiaokang Lv: Writing – review & editing, Writing – original draft. **Min Zhang:** Data curation. **Ke Ji:** Data curation. **Chuanshe Zhou:** Writing – review & editing. **Jinling Hua:** Conceptualization.

Availability of data and materials

Data may be provided following request to the corresponding author.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aninu.2024.11.014.

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