Pesquisa Agropecuária Brasileira

Animal Science/ Original Article

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Nutraceutical supplementation on rumen fermentation and growth performance of goats under semiarid tropical conditions

Abstract – The objective of this work was to evaluate the integrated effects of nutraceutical dietary supplementation on rumen fermentation characteristics, oxidative stress biomarkers, hematological responses, and growth performance in goats (*Capra hircus*) raised under the semiarid tropical conditions of Sumbawa, Indonesia. Twenty-four male goats aged 8 to 10 months were randomly assigned to four dietary treatments: basal diet without supplementation (control), and basal diet supplemented with three different nutraceutical formulations containing plant-derived bioactive compounds and yeast-based additives. The feeding trial lasted for 90 days. Rumen pH, volatile fatty acids (VFA), ammonia nitrogen, oxidative stress biomarkers (malondialdehyde and superoxide dismutase), hematological variables, and average daily gain (ADG) were measured. Compared with the control diet, nutraceutical supplementation increased total VFA concentration by 18–24% and NH_3-N availability, but decreased the acetate to propionate ratio ($p<0.05$). Supplemented goats also exhibited a lower lipid peroxidation and a higher antioxidant activity. Hematological indicators remained within physiological ranges, but showed improved immune stability and protein status. In addition, growth performance increased significantly, resulting in a higher ADG and improved feed conversion efficiency. These findings show that nutraceutical dietary strategies can simultaneously enhance rumen microbial activity, antioxidant defense mechanisms, and productive performance in goats raised under semiarid tropical production systems.

Index terms: *Capra hircus*, average daily gain, hematology, oxidative stress, rumen fermentation.

Rezki Amalyadi ✉
Universitas Mataram, Faculty of Animal Science, Indonesia.
E-mail: rezkiamalyadi@staff.unram.ac.id

✉ Corresponding author

Received
March 12, 2026

Accepted
June 15, 2026

How to cite
AMALYADI, R. Nutraceutical supplementation on rumen fermentation and growth performance of goats under semiarid tropical conditions. **Pesquisa Agropecuária Brasileira**, v.61, e04421, 2026. DOI: https://doi.org/10.1590/S1678-3921.pab2026.v61.04421.

Suplementação com nutracêuticos na fermentação ruminal e no desempenho de crescimento de cabras em condições tropicais semiáridas

Resumo – O objetivo deste trabalho foi avaliar os efeitos combinados da suplementação alimentar com nutracêuticos nas características da fermentação ruminal, nos biomarcadores de estresse oxidativo, nas respostas hematológicas e no desempenho de crescimento de bodes (*Capra hircus*) criados em condições tropicais semiáridas em Sumbawa, Indonésia. Vinte e quatro bodes, com idade entre 8 e 10 meses de idade, foram distribuídos aleatoriamente por quatro tratamentos alimentares: dieta basal sem suplementação (controle), e dieta basal suplementada com três diferentes formulações nutracêuticas contendo compostos bioativos de origem vegetal e aditivos à base de levedura. O ensaio alimentar durou 90 dias. Foram medidos pH ruminal, ácidos graxos voláteis (AGV), nitrogênio amoniacal, biomarcadores de estresse oxidativo

This is an open-access article distributed under the Creative Commons Attribution 4.0 International License

(malondialdeído e superóxido dismutase), variáveis hematológicas e ganho médio diário. Em comparação com a dieta de controle, a suplementação com nutracêuticos aumentou a concentração total de AGV em 18–24% e a disponibilidade de NH_3-N, mas reduziu a relação acetato/propionato ($p<0,05$). Os bodes suplementados também apresentaram menor peroxidação lipídica e maior atividade antioxidante. Os indicadores hematológicos permaneceram nos intervalos fisiológicos, mas apresentaram estabilidade imunológica e estado proteico melhorados. O desempenho de crescimento aumentou significativamente, tendo resultado em maior ganho médio diário e melhor eficiência de conversão alimentar. Esses resultados mostram que estratégias dietéticas nutracêuticas podem simultaneamente melhorar a atividade microbiana do rúmen, os mecanismos de defesa antioxidante e o desempenho produtivo em bodes criados em sistemas de produção tropicais semiáridos.

Termos para indexação: *Capra hircus*, ganho médio diário, hematologia, estresse oxidativo, fermentação ruminal.

Introduction

Goat (*Capra hircus*) production systems in semi-arid regions are highly dependent on nutritional management to sustain productivity under fluctuating feed availability and climatic stress (Faji Dida, 2023). In Sumbawa, Indonesia, seasonal forage scarcity and high ambient temperatures can compromise rumen efficiency, immune competence, and growth performance in smallholder goat systems (Joy et al., 2020). Optimizing dietary strategies is therefore critical for maintaining physiological stability and production efficiency under these environmental constraints. Rumen fermentation variables, including ruminal pH, volatile fatty acids (VFA), and ammonia nitrogen, are key indicators of microbial activity and nutrient utilization efficiency in ruminants (Ahmed et al., 2024; Wang, 2025). Alterations in diet composition can substantially modify fermentation end products, influencing both energy supply and nitrogen metabolism.

Beyond rumen function, dietary interventions can also influence systemic oxidative balance and immune status. Nutritional imbalances and metabolic challenges can elevate reactive oxygen species, thereby increasing lipid peroxidation markers such as malondialdehyde (MDA); conversely, antioxidant enzymes, including superoxide dismutase (SOD), serve as critical endogenous defense mechanisms (Allen, 2020; Jain & Shakkarpude, 2024). Feed additives rich in bioactive compounds, such as flavonoids, polyphenols, condensed tannins, curcuminoids, and gingerols, or those designed to optimize protein-energy synchronization, have been shown to modulate oxidative biomarkers and improve hematological profiles in goats (Choubey et al., 2016; Zhang et al., 2024). Furthermore, leukocyte counts and serum total protein concentrations reflect immunological responsiveness and nutritional adequacy (Johns & Heller, 2021).

Growth performance, commonly measured as average daily gain (ADG), integrates metabolic efficiency, rumen fermentation dynamics, and systemic health status (Dai & Faciola, 2019). Although previous studies have separately evaluated rumen fermentation, oxidative stress biomarkers, and hematological indices, integrated investigations linking these variables within semiarid tropical production systems remain limited (Samal et al., 2015; Johns & Heller, 2021). Understanding these interrelationships is essential for developing evidence-based feeding strategies that enhance both animal health and productivity.

Despite the growing body of literature on nutritional interventions in small ruminants, most studies have examined rumen fermentation characteristics, oxidative stress biomarkers, and growth performance as independent responses. In addition, yeast-based and phytogenic additives have been widely investigated for improving rumen fermentation or antioxidant status individually, although studies evaluating their integrated effects on rumen microbial activity, oxidative balance, hematological responses, and growth performance in goats raised under semi-arid tropical conditions remain scarce. Furthermore, the physiological link between improved rumen fermentation and systemic oxidative status has not been sufficiently explored in small ruminant production systems.

The objective of this work was to evaluate the integrate effects of nutraceutical dietary supplementation on rumen fermentation characteristics, oxidative stress biomarkers, hematological responses, and growth performance in goats raised under the semiarid tropical conditions of Sumbawa, Indonesia.

Materials and Methods

The study was conducted in Sumbawa Regency, West Nusa Tenggara, Indonesia (approximately 8°45'–9°15'S, 117°05[–118°20'E). The region is characterized by a semiarid tropical climate with a prolonged dry season extending from May to November. During the experimental period, the ambient temperature ranged from 24 to 36°C, with annual average temperatures of 27–32°C, while the mean relative humidity ranged from 70 to 80%. These environmental conditions frequently limit forage availability and quality, requiring adaptive nutritional and feeding strategies for small-ruminant production systems. All experimental procedures involving animals were approved by the Research Ethics Committee of Sumbawa University of Technology (Approval No. 0324/UN18.F2/EC/2025). Animal management and sampling procedures complied with internationally recognized standards for animal welfare and livestock research.

A total of 24 clinically healthy male goats aged 8–10 months with a mean initial body weight of 18.6±1.5 kg were used in the experiment. Animals within this age range were selected because they represent the post-weaning growth phase, during which rumen function is fully established and growth rates remain relatively high. Consequently, physiological responses to dietary supplementation, such as changes in rumen fermentation, oxidative status, hematological variables, and weight gain, can be more clearly detected than in mature animals.

The feeding trial lasted for 90 days, consisting of a 14-day adaptation period followed by 76 days of data collection. All goats were housed individually in shaded pens measuring 1.5×1.2 m, equipped with feed and water troughs and non-slip flooring. The animals had ad libitum access to fresh water throughout the study.

The goats were randomly allocated to four dietary treatments in a completely randomized design, with six animals assigned to each treatment. These treatments were: basal diet without supplementation (control); and basal diet supplemented with three nutraceutical formulations containing plant-derived bioactive compounds and yeast-based additives (treatments A, B, and C). Nutraceutical supplements were incorporated daily into the concentrate portion of the diet at 2% of dry matter intake (DMI) and thoroughly mixed immediately before feeding to ensure a uniform consumption by all animals.

The basal diet consisted of local grass hay (*Panicum maximum* Jacq.), legume hay [*Leucaena leucocephala* (Lam.) de Wit], and a concentrate consisting of a commercial mix of energy and protein sources (Table 1). The diet was formulated in a 60:40 forage to concentrate ratio across all treatments in order to meet or exceed the maintenance and growth requirements for goats based on nutrient standards for small ruminants (NRC, 2007). The chemical composition of feed ingredients, including dry matter (DM), crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF), was determined according to the procedures of Association of Official Analytical Chemists (AOAC, 2019) and Van Soest et al. (1991). Rumen VFA concentrations were analyzed by gas chromatography following the method described by Erwin et al. (1961), while NH_3-N concentration was determined using the phenol–hypochlorite procedure of Broderick & Kang (1980). Serum total protein was measured using the biuret method (Doumas et al., 1981). Moreover, MDA and SOD were quantified using commercial assay kits according to the manufacturers' protocols and the analytical procedures described by Jain & Shakkarpude (2024). Hematological variables were determined using an automated veterinary hematology analyzer following the recommendations of Brooks et al. (2022).

The evaluated nutraceutical supplements consisted of dietary formulations designed to enhance rumen microbial activity and antioxidant capacity. In treatment A, 1×10^9 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture were combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; in treatment B, a phytogenic mixture was composed of *Curcuma longa* L., *Zingiber officinale* Roscoe, and *Andrographis paniculata* (Burm.f.) Wall. ex Nees extracts with a standardized

Table 1. Composition and nutrient content of the basal diet without supplementation.

Ingredient	% Dry mass
Grass hay	45
Legume hay	15
Maize	20
Soybean meal	12
Wheat bran	6
Mineral premix	2

content of 8% flavonoids and 4% condensed tannins; and, in treatment C, the formulation combined 1×10^9 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium. All supplements were incorporated into the concentrate portion of the diet at 2% of DMI and thoroughly incorporated into the concentrate portion of the basal diet to ensure uniform intake. These formulations were selected based on their documented potential to modulate rumen microbial ecology, improve antioxidant defenses, and enhance nutrient utilization in ruminants. The feed ingredients were analyzed for DM, CP, NDF, and ADF before feeding, using standard proximate analysis procedures. Feed was offered twice a day at 8 a.m. and 4 p.m. The amounts of feed offered and refused were measured daily to calculate DMI. Feed intake data were recorded throughout the trial period to monitor consumption patterns and adjust feeding if necessary.

Rumen fluid samples were collected on days 45 and 90 of the trial using an oral stomach tube connected to a vacuum pump. Sampling was conducted at 0 hour (pre-feeding) and at 4 and 8 hours post-feeding. Immediately after collection, rumen fluid was filtered through four layers of cheesecloth. A 10 mL aliquot was used for VFA analysis and preserved with 1.0 mL of 25% metaphosphoric acid, while a separate 9 aliquot was stored for NH_3-N determination. Volatile fatty acids were separated and quantified by gas chromatography following standard procedures widely used in contemporary rumen fermentation studies (Qi & Wang, 2024; Rabee et al., 2024). The NH_3-N concentration was determined using the phenol-hypochlorite colorimetric method according to established protocols commonly applied in ruminant nutrition research (Samal et al., 2015; Ahmed et al., 2024).

Blood samples were collected from the jugular vein on days 0, 45, and 90 before morning feeding. Samples were transferred into EDTA blood collection vacuum tubes for hematological analyses and plain tubes for serum separation. Serum was obtained by centrifugation at 3,000 × g for 15 min and stored at -20°C until analysis. Serum total protein concentration was determined using the biuret method. Oxidative stress biomarkers, including MDA and SOD, were quantified using commercially available diagnostic kits and spectrophotometric procedures according to the manufacturers' instructions. Similar analytical approaches have been widely employed in recent studies evaluating oxidative status and antioxidant responses in goats and other ruminants (Chen et al., 2024; Jain & Shakkarpude, 2024; Zhang et al., 2024). Hematological variables, including total leukocyte count and differential leukocyte percentages, were analyzed using an automated veterinary hematology analyzer calibrated for caprine blood following current veterinary laboratory standards (Brooks et al., 2022).

Goats were weighed at the start of the experiment and every two weeks thereafter using a calibrated livestock scale. ADG was calculated in grams per day for each animal according to the following equation:

$$\text{ADG} = \frac{\text{Final BW} - \text{Initial BW}}{\text{Experimental period}} \text{ x } 1{,}000$$

Where final BW and initial BW represent the final body weight and initial body weight, respectively, both expressed in kilograms; and the experimental period is expressed in days. Body weight measurements were taken in the morning before feeding to minimize diurnal variation.

All collected data were analyzed using the analysis of variance (ANOVA) for a completely randomized design. Fixed effects included dietary treatment, sampling day, and their interaction. When significant treatment effects were detected ($p<0.05$), the means were separated using Tukey's honest significant difference test. Repeated ANOVA measures were applied to variables measured over time, including rumen fermentation variables and blood biomarkers. Statistical analyses were performed using the IBM SPSS Statistics, version 26.0, software (IBM Corp., Armonk, NY, USA). Prior to the analysis, data were examined for normality and homogeneity of variance using Shapiro-Wilk's and Levene's tests, respectively. The statistical model applied for the analysis of treatment effects was:

$$Y_{ijk} = \mu + T_i + D_j + (T \times D)_{ij} + e_{ijk}$$

where Y_{ijk} is the observed variable, μ is the overall mean, T_i is the fixed effect of dietary treatment, e_{ijk} is the random error, T is treatment, and D is day.

Results and Discussion

Dietary interventions influenced rumen fermentation characteristics (Figure 1 and Table 2). Goats treated with nutraceutical supplementation exhibited a more stable ruminal environment compared with those treated with the control diet. Ruminal pH measured 4 hours post-feeding ranged from 6.21 in the control group to 6.48 in treatment C, with all supplemented treatments showing higher pH values than the control ($p = 0.018$). This finding indicates improved rumen buffering capacity and a reduced risk of suboptimal fermentation conditions.

Total VFA concentration notably increased in response to dietary supplementation. The control group showed a mean total VFA concentration of 82.4 mmol L^{-1}, whereas treatments A, B, and C recorded concentrations of 91.6, 96.8, and 102.3 mmol L^{-1}, respectively ($p = 0.004$). The highest VFA production was observed in treatment C, representing an increase of approximately 24% relative to the control diet.

NH_3-N concentration differed significantly among treatments ($p = 0.021$), with supplemented goats exhibiting ruminal NH_3-N levels ranging from 17.8 to 19.2 mg dL^{-1}, while the control group achieved 14.1 mg dL^{-1}. This increase indicates enhanced nitrogen availability for microbial protein synthesis. In addition, the acetate to propionate ratio decreased significantly in all supplemented treatments, declining from 3.21 in the control group to 2.98, 2.85, and 2.73 in treatments A, B, and C, respectively ($p = 0.033$). This shift toward a lower acetate to propionate ratio suggests improved fermentation efficiency and greater energetic utilization of dietary substrates.

The observed improvements in rumen fermentation indicate that nutraceutical supplementation enhanced microbial activity and energy availability within the rumen ecosystem. Similar responses have been reported following yeast culture supplementation, which increased ruminal pH and short-chain fatty acid concentrations while mitigating the negative effects of environmental stress on rumen function (Chen et al.,

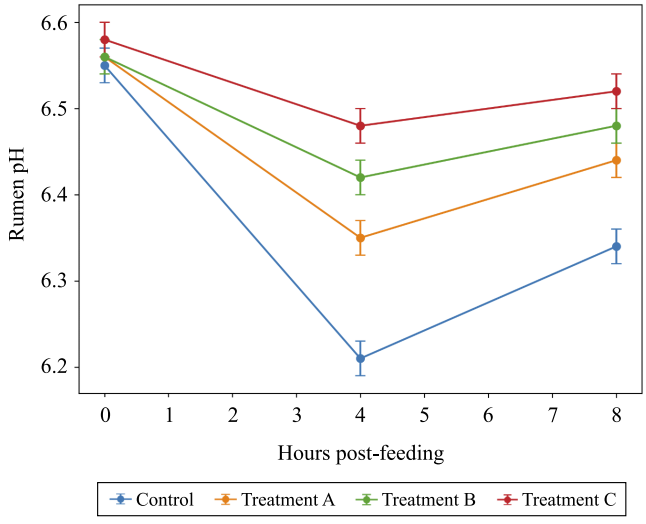

Figure 1. Ruminal pH at 0, 4, and 8 hours post-feeding across all dietary treatments applied to goats (*Capra hircus*) raised under the semiarid tropical conditions of Indonesia. Each treatment consisted of different neutraceutical formulations: Treatment A, 1×10^9 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; Treatment B, phytogenic mixture composed of *Curcuma longa*, *Zingiber officinale*, and *Andrographis paniculata* extracts with a standardized content of 8% flavonoids and 4% condensed tannins; and Treatment C, 1×10^9 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium.

Table 2. Values for rumen fermentation variables across different dietary treatments applied to goats (*Capra hircus*) raised under the semiarid tropical conditions of Indonesia[1].

Variable[2]	Control	Treatment A	Treatment B	Treatment C	SEM[3]	p-value
pH 4 hours after feeding	6.21a	6.35b	6.42b	6.48b	0.07	0.018
Total VFA (mmol L^{-1})	82.4a	91.6b	96.8b	102.3c	3.12	0.004
NH_3-N (mg dL^{-1})	14.1a	17.8b	18.4b	19.2b	0.95	0.021
Acetate to propionate ratio	3.21a	2.98b	2.85b	2.73b	0.11	0.033

[1]Means followed by different letters, in the rows, do differ from each other by Tukey's test, at $p<0.05$. [2]VFA, volatile fatty acids; and NH_3-N, ammonia nitrogen. [3]SEM, standard error of the mean. Each treatment consisted of different neutraceutical formulations: Treatment A, 1×10^9 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; Treatment B, phytogenic mixture composed of *Curcuma longa*, *Zingiber officinale*, and *Andrographis paniculata* extracts with a standardized content of 8% flavonoids and 4% condensed tannins; and Treatment C, 1×10^9 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium.

2024; Li et al., 2024; Qi & Wang, 2024). Enhanced VFA production is particularly important because acetate and propionate serve as major substrates for fatty acid synthesis and gluconeogenesis, thereby influencing growth performance and nutrient utilization efficiency. Furthermore, phytogenic compounds may alter rumen microbial ecology by promoting fibrolytic populations and increasing fermentation end products (Zhu et al., 2017; Yin et al., 2021; Zhao et al., 2023).

Serum oxidative stress biomarkers were influenced by dietary supplementation (Figure 2 and Table 3). MDA, a lipid peroxidation marker, showed the highest value in the control group at 5.84 nmol L^{-1} and progressively decreased with supplementation. Treatments A and B showed 4.92 and 4.51 nmol L^{-1}, respectively, whereas treatment C exhibited the lowest concentration at 4.12 nmol L^{-1} ($p = 0.001$). Conversely, SOD activity increased in response to nutraceutical supplementation ($p = 0.002$), rising from 78.3 U mL^{-1} in the control group to 92.6, 101.4, and 108.9 U mL^{-1} in treatments A, B, and C, respectively. Temporal analysis revealed a gradual reduction in MDA concentrations throughout the experimental period in the supplemented groups, whereas MDA levels remained relatively stable in the control group (Figure 2).

The simultaneous increase in SOD activity combined with the reduction in MDA levels indicate enhanced antioxidant capacity and reduced oxidative damage. These findings agree with previous works showing that antioxidant-rich dietary supplements and probiotic-based feed additives increase the activity of endogenous antioxidant enzymes and reduce lipid peroxidation in goats (Wang et al., 2022; Ogbuewu & Mbajiorgu, 2023; Gaafar et al., 2026). Oxidative stress can compromise cellular integrity, immune competence, and productive performance, particularly under conditions of nutritional and environmental challenge (Garcia et al., 2017; Peng et al., 2026). Therefore, the improved antioxidant status observed in supplemented goats suggests that nutraceutical

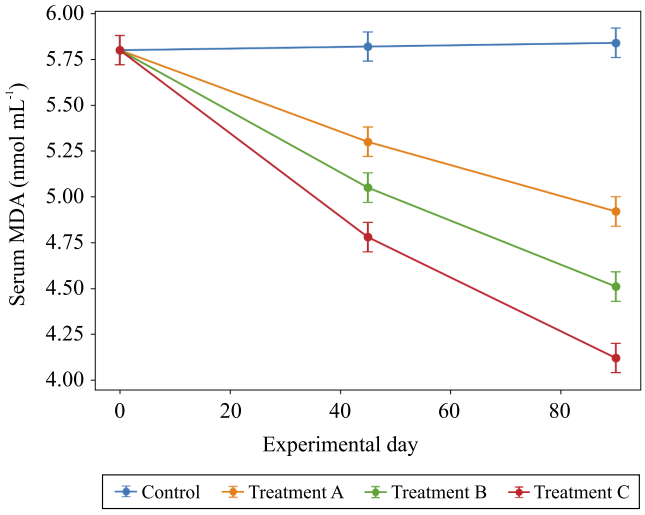

Figure 2. Changes in serum malondialdehyde (MDA) concentration on days 0, 45, and 90 of the experimental period due to dietary treatments applied to goats (*Capra hircus*) raised under the semiarid tropical conditions of Indonesia. Each treatment consisted of different neutraceutical formulations: Treatment A, 1×10^9 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; Treatment B, phytogenic mixture composed of *Curcuma longa*, *Zingiber officinale*, and *Andrographis paniculata* extracts with a standardized content of 8% flavonoids and 4% condensed tannins; and Treatment C, 1×10^9 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium.

Table 3. Values for serum oxidative stress biomarkers across different dietary treatments applied to goats (*Capra hircus*) raised under the semiarid tropical conditions of Indonesia[(1)].

Variable[(2)]	Control	Treatment A	Treatment B	Treatment C	SEM	p-value
MDA (nmol mL^{-1})	5.84a	4.92b	4.51b	4.12c	0.21	0.001
SOD (U mL^{-1})	78.3a	92.6b	101.4c	108.9c	4.55	0.002

[(1)]Means followed by different letters, in the rows, do differ from each other by Tukey's test, at $p<0.05$. [(2)]MDA, malondialdehyde; SOD, superoxide dismutase; and SEM, standard error of the mean. Each treatment consisted of different neutraceutical formulations: Treatment A, 1×10^9 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; Treatment B, phytogenic mixture composed of *Curcuma longa*, *Zingiber officinale*, and *Andrographis paniculata* extracts with a standardized content of 8% flavonoids and 4% condensed tannins; and Treatment C, 1×10^9 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium.

compounds contributed to greater physiological resilience by strengthening endogenous defense mechanisms against reactive oxygen species.

Hematological variables remained within physiological ranges across all treatments. However, several indicators were influenced by nutraceutical supplementation (Figure 3 and Table 4). Total leukocyte counts decreased slightly in the nutraceutical supplemented groups compared with the control ($p = 0.028$), declining from 11.8×10^3 μL^{-1} to values ranging between 9.9 and 10.6×10^3 μL^{-1}. Serum total protein concentration increased with nutraceutical supplementation ($p = 0.009$), rising from 6.21 g dL^{-1} in the control group to 6.78, 6.95, and 7.14 g dL^{-1} in treatments A, B, and C, respectively. Similarly, the neutrophil to lymphocyte ratio decreased significantly from 0.72 in the control group to values between 0.58 and 0.64 in supplemented goats ($p = 0.031$), indicating improved physiological stability and reduced systemic stress.

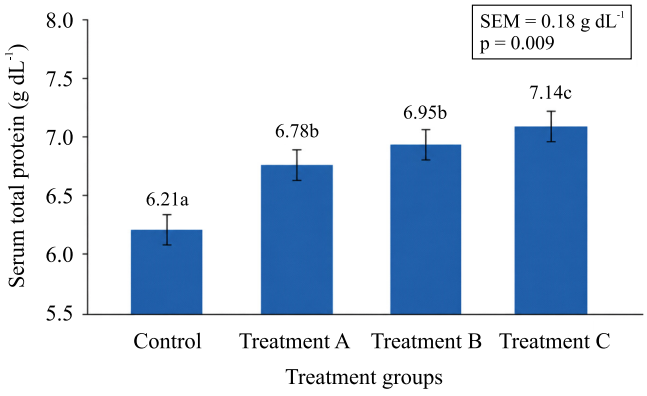

Figure 3. Comparison of serum total protein levels at day 90 across dietary treatments applied to goats (*Capra hircus*) under the semiarid tropical conditions of Indonesia. Each treatment consisted of different neutraceutical formulations: Treatment A, 1×109 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; Treatment B, phytogenic mixture composed of *Curcuma longa*, *Zingiber officinale*, and *Andrographis paniculata* extracts with a standardized content of 8% flavonoids and 4% condensed tannins; and Treatment C, 1×109 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium.

The hematological responses suggest that dietary supplementation improved both protein metabolism and immune homeostasis. The increase in serum total protein likely reflects enhanced nitrogen utilization and synthesis of physiologically important proteins that are involved in immune regulation and in tissue maintenance. Comparable improvements in hematological and immunological indicators have been reported following supplementation with rumen-protected nutrients and functional feed additives, which can modulate systemic physiological responses beyond the rumen environment (Swartz et al., 2022; Asadi et al., 2025). The reduction in both leukocyte counts and neutrophil to lymphocyte ratio further suggests a lower inflammatory burden and an improved adaptation to environmental stressors.

Growth performance indicators were improved by nutraceutical supplementation during the 90 day feeding trial (Figure 4 and Table 5). Initial body weights were comparable among treatments, ranging from 18.5 to 18.7 kg ($p = 0.981$), confirming uniform baseline conditions. However, final body weights differed significantly ($p = 0.003$), reaching 24.1, 26.8, 27.9, and 29.3 kg in the control group and treatments A, B, and C, respectively. ADG followed a similar pattern, increasing from 61 g per day in the control group to

Table 4. Values for hematological variables and serum total protein across different dietary treatments applied to goats (*Capra hircus*) raised under the semiarid tropical conditions of Indonesia[(1)].

Variable	Control	Treatment A	Treatment B	Treatment C	SEM[(2)]	p-value
Leukocytes ($\times 10^3$ μL^{-1})	11.8a	10.6b	10.2b	9.9b	0.52	0.028
Serum total protein (g dL^{-1})	6.21a	6.78b	6.95b	7.14c	0.18	0.009
Neutrophil to lymphocyte ratio	0.72a	0.64b	0.61b	0.58b	0.03	0.031

[(1)]Means followed by different letters, in the rows, do differ from each other by Tukey's test, at $p<0.05$. [(2)]SEM, standard error of the mean. Each treatment consisted of different neutraceutical formulations: Treatment A, 1×10^9 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; Treatment B, phytogenic mixture composed of *Curcuma longa*, *Zingiber officinale*, and *Andrographis paniculata* extracts with a standardized content of 8% flavonoids and 4% condensed tannins; and Treatment C, 1×10^9 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium.

90, 104, and 119 g per day in treatments A, B, and C, respectively ($p = 0.001$). The feed conversion ratio also improved significantly ($p = 0.017$), decreasing from 8.4 in the control group to 7.1, 6.8, and 6.3 in treatments A, B, and C, respectively. Furthermore, correlation analysis revealed a positive association between total VFA concentration and ADG ($r = 0.67$, $p < 0.05$), indicating that enhanced rumen fermentation efficiency was closely linked to improved growth performance (Figure 4).

The positive impact on growth performance highlights the integrated benefits of improved rumen fermentation, antioxidant status, and nutrient utilization efficiency. Previous works have demonstrated that yeast cultures, phytogenic additives, and other functional feed supplements can improve ADG and feed efficiency in goats through enhanced digestive and metabolic processes (Jiang et al., 2019; Lugar et al., 2019). The positive correlation between VFA concentration and ADG observed in this study supports the concept that greater fermentation efficiency increases the availability of metabolizable energy for tissue accretion and growth.

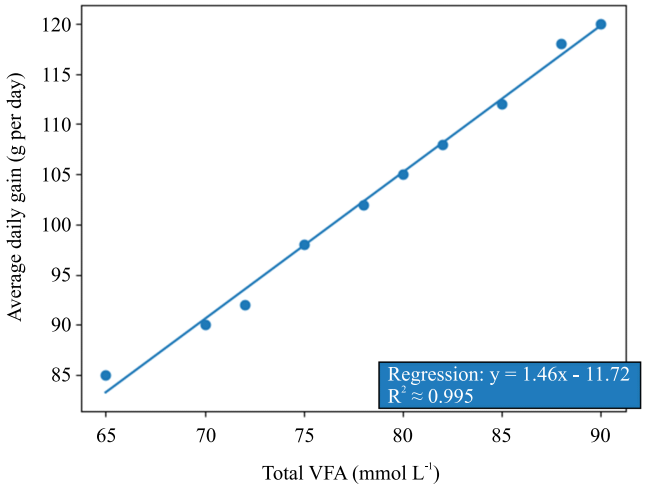

Figure 4. Relationship between total volatile fatty acids (VFA) and average daily gain in goats (*Capra hircus*) subjected to dietary supplementation under the semiarid tropical conditions of Indonesia. R^2, coefficient of determination.

The obtained results likely reflect interconnected mechanisms operating at the ruminal, metabolic, and systemic levels. An enhanced VFA production, a stabilized ruminal pH, a reduced oxidative damage, and an improved hematological homeostasis collectively create physiological conditions favorable for sustained growth and productivity. These findings are consistent with broader evidence showing that probiotics, phytogenic compounds, and antioxidant-rich feed additives can improve nutrient utilization, reduce metabolic stress, and enhance overall animal performance (Fan et al., 2021; Sangkaew et al., 2025). Furthermore, nutritional modulation of rumen microbial ecology through phytogenic compounds and condensed tannins has been shown to influence host metabolism and health outcomes (Rabee et al., 2024).

Notably, the present findings extend current knowledge by demonstrating the interconnected effects of nutraceutical supplementation on rumen fermentation, oxidative stress regulation, hematological homeostasis, and growth performance in goats raised under semiarid tropical conditions. While previous works have generally evaluated these physiological responses independently, the present

Table 5. Growth performance of goats (*Capra hircus*) subjected to supplementation with different neutraceutical formulations during a 90 day trial under the semiarid tropical conditions of Indonesia[1].

Variable[2]	Control	Treatment A	Treatment B	Treatment C	SEM[3]	p-value
Initial BW (kg)	18.6	18.7	18.5	18.6	0.32	0.981
Final BW (kg)	24.1a	26.8b	27.9b	29.3c	0.76	0.003
ADG (g per day)	61a	90b	104b	119c	6.2	0.001
FCR	8.4a	7.1b	6.8b	6.3c	0.41	0.017

[1]Means followed by different letters, in the rows, do differ from each other by Tukey's test, at $p<0.05$. [2]BW, body weight; ADG, average daily gain; and FCR, feed conversion ratio. [3]SEM, standard error of the mean. Each treatment consisted of different neutraceutical formulations: Treatment A, 1×10^9 CFU g^{-1} *Saccharomyces cerevisiae* CNCM I-1077 yeast culture combined with a plant-derived polyphenol extract containing 120 mg g^{-1} total phenolics; Treatment B, phytogenic mixture composed of *Curcuma longa*, *Zingiber officinale*, and *Andrographis paniculata* extracts with a standardized content of 8% flavonoids and 4% condensed tannins; and Treatment C, 1×10^9 CFU g^{-1} yeast culture, herbal extracts, and a mineral premix containing zinc, copper, and selenium.

study simultaneously assessed digestive, biochemical, physiological, and productive indicators within a single experimental framework.

The observed association between enhanced rumen fermentation, improved antioxidant status, greater hematological stability, and superior growth performance suggests the existence of coordinated biological mechanisms linking rumen function with systemic physiological resilience. These integrated responses highlight the potential of nutraceutical supplementation as a practical nutritional strategy for improving both productivity and adaptive capacity in smallholder goat production systems exposed to challenging semiarid environments. Future studies incorporating metagenomic, metabolomic, and dose-response approaches are warranted to elucidate the mechanistic pathways underlying these responses and to refine evidence-based feeding recommendations.

Conclusions

1. Nutraceutical dietary supplementation significantly enhances rumen fermentation efficiency, reduces oxidative stress indicators, and improves overall growth performance in goats (*Capra hircus*) raised under semiarid tropical conditions.

2. Integrated nutraceutical feeding strategies represent a viable nutritional approach to improve productivity and physiological resilience in smallholder goat production systems.

References

AHMED, M.G.; ELWAKEEL, E.A.; EL-ZARKOUNY, S.Z.; AL-SAGHEER, A.A. Environmental impact of phytobiotic additives on greenhouse gas emission reduction, rumen fermentation manipulation, and performance in ruminants: an updated review. **Environmental Science and Pollution Research**, v.31, p.37943-37962, 2024. DOI: https://doi.org/10.1007/s11356-024-33664-5.

ALLEN, M.S. Review: control of feed intake by hepatic oxidation in ruminant animals: integration of homeostasis and homeorhesis. **Animal**, v.14, p.s55-s64, 2020. Suppl.1. DOI: https://doi.org/10.1017/S1751731119003215.

AOAC. Association of Official Analytical Chemists. **AOAC guidelines for single laboratory validation of chemical methods for dietary supplements and botanicals**. Gaithersburg: Association of Official Analytical Chemists, 2019. p.5-13.

ASADI, M.; BOKHARAEIAN, M.; FARD, H.M. Effects of dietary rumen-protected choline on stress alleviation, antioxidant modulation, and haematological, immunological, and offspring performance in transitioning goats. **Veterinary Medicine and Science**, v.11, e70524, 2025. DOI: https://doi.org/10.1002/vms3.70524.

BRODERICK, G.A.; KANG, J.H. Automated simultaneous determination of ammonia and total amino acids in ruminal fluid and in vitro media. **Journal of Dairy Science**, v.63, p.64-75, 1980. DOI: https://doi.org/10.3168/jds.S0022-0302(80)82888-8.

BROOKS, M.B.; HARR, K.E.; SEELIG, D.M.; WARDROP, K.J.; WEISS, D.J. (Ed.). **Schalm's Veterinary Hematology**. 7th ed. Hoboken: Wiley-Blackwell, 2022. DOI: https://doi.org/10.1002/9781119500537.

CHEN, H.; LIU, S.; LI, S.; LI, D.; LI, X.; XU, Z.; LIU, D. Effects of yeast culture on growth performance, immune function, antioxidant capacity and hormonal profile in Mongolian ram lambs. **Frontiers in Veterinary Science**, v.11, art.1424073, 2024. DOI: https://doi.org/10.3389/fvets.2024.1424073.

CHOUBEY, M.; PATTANAIK, A.K.; BALIYAN, S.; DUTTA, N.; JADHAV, S.E.; SHARMA, K. Dietary supplementation of a novel phytogenic feed additive: effects on nutrient metabolism, antioxidant status and immune response of goats. **Animal Production Science**, v.56, p.1612-1621, 2016. DOI: https://doi.org/10.1071/AN14770.

DAI, X.; FACIOLA, A.P. Evaluating strategies to reduce ruminal protozoa and their impacts on nutrient utilization and animal performance in ruminants: a meta-analysis. **Frontiers in Microbiology**, v.10, art.2648, 2019. DOI: https://doi.org/10.3389/fmicb.2019.02648.

DOUMAS, B.T.; BAYSE, D.D.; CARTER, R.J.; PETERS JR, T.; SCHAFFER, R. A candidate reference method for determination of total protein in serum. I. Development and validation. **Clinical Chemistry**, v.27, p.1642-1650, 1981. DOI: https://doi.org/10.1093/clinchem/27.10.1642.

ERWIN, E.S.; MARCO, G.J.; EMERY, E.M. Volatile fatty acid analyses of blood and rumen fluid by gas chromatography. **Journal of Dairy Science**, v.44, p.1768-1771, 1961. DOI: https://doi.org/10.3168/JDS.S0022-0302(61)89956-6.

FAJI DIDA, M. Strategies for goat feeding and management during drought. In: KUKOVICS, S. (Ed.). **Goat Science**: environment, health and economy. London: IntechOpen, 2023. p.123-125. DOI: https://doi.org/10.5772/intechopen.101161.

FAN, Q.; CUI, X.; WANG, Z.; CHANG, S.; WANAPAT, M.; YAN, T.; HOU, F. Rumen microbiota of tibetan sheep (*Ovis aries*) adaptation to extremely cold season on the Qinghai-Tibetan plateau. **Frontiers in Veterinary Science**, v.8, art.673822, 2021. DOI: https://doi.org/10.3389/fvets.2021.673822.

GAAFAR, H.M.; BASSIOUNI, M.I.; ALI, M.F.; SHAMS, A.S.; MESBAH, R.A.; TAHA, S.S. Effect of yeast cell wall additive on digestion, rumen fermentation, some blood biochemical and growth performance of Baladi goat kids. **Egyptian Journal of Veterinary Sciences**, v.57, p.1-12, 2026.

GARCIA, M.; BRADFORD, B.J.; NAGARAJA, T.G. Invited review: ruminal microbes, microbial products, and systemic inflammation. **The Professional Animal Scientist**, v.33, p.635-650, 2017. DOI: https://doi.org/10.15232/pas.2017-01663.

JAIN, A.; SHAKKARPUDE, J. Oxidative stress: a biomarker for animal health and production: a review. **Indian Journal of Animal Research**, v.58, p.1-12, 2024. DOI: https://doi.org/10.18805/IJAR.B-5300.

JIANG, Z.; WAN, Y.; LI, P.; XUE, Y.; CUI, W.; CHEN, Q.; CHEN, J.; WANG, F.; MAO, D. Effect of curcumin supplement in summer diet on blood metabolites, antioxidant status, immune response, and testicular gene expression in Hu sheep. **Animals**, v.9, art.720, 2019. DOI: https://doi.org/10.3390/ani9100720.

JOHNS, J.; HELLER, M. Hematologic conditions of small ruminants. **Veterinary Clinics of North America: Food Animal Practice**, v.37, p.183-197, 2021. DOI: https://doi.org/10.1016/j.cvfa.2020.10.004.

JOY, A.; DUNSHEA, F.R.; LEURY, B.J.; CLARKE, I.J.; DIGIACOMO, K.; CHAUHAN, S.S. Resilience of small ruminants to climate change and increased environmental temperature: a review. **Animals**, v.10, art.867, 2020. DOI: https://doi.org/10.3390/ANI10050867.

LI, X.; AN, N.; CHEN, H.; LIU, D. Effects of yeast culture on growth performance, antioxidant capacity, immune function, and intestinal microbiota structure in Simmental beef cattle. **Frontiers in Veterinary Science**, v.11, art.1533081, 2024. DOI: https://doi.org/10.3389/fvets.2024.1533081.

LUGAR, D.W.; HARLOW, K.E.; HUNDLEY, J.; GONCALVES, M.; BERGSTROM, J.; STEWART, K.R. Effects of increased levels of supplemental vitamins during the summer in a commercial artificial insemination boar stud. **Animal**, v.13, p.2556-2568, 2019. DOI: https://doi.org/10.1017/S1751731119001150.

NRC. National Research Council. **Nutrient requirements of small ruminants**: sheep, goats, cervids, and new world camelids. Washington: The National Academies Press, 2007.

OGBUEWU, I.P.; MBAJIORGU, C.A. Meta-analysis of *Saccharomyces cerevisiae* on enhancement of growth performance, rumen fermentation and haemato-biochemical characteristics of growing goats. **Heliyon**, v.9, e14178, 2023. DOI: https://doi.org/10.1016/j.heliyon.2023.e14178.

PENG, C.; XIE, H.; SU, N.; HE, Y.; YUAN, C.; ZHAO, C.; ZHANG, W.; LIU, B.; ZHANG, S.; FU, Y.; SUN, X.; HU, X. Ruminal microbial dysbiosis induces the development of gastrointestinal inflammation through the activation of ferritinophagy-ferroptosis via the NOCA4/FTH pathway. **International Immunopharmacology**, v.169, art.115816, 2026. DOI: https://doi.org/10.1016/j.intimp.2025.115816.

QI, P.; WANG, L. Effect of adding yeast cultures to high-grain conditions on production performance, rumen fermentation profile, microbial abundance, and immunity in goats. **Animals**, v.14, art.1799, 2024. DOI: https://doi.org/10.3390/ani14121799.

RABEE, A.E.; GHANDOUR, M.M.M.; SALLAM, A.; ELWAKEEL, E.A.; MOHAMMED, R.S.; SABRA, E.A.; ABDEL-WAHED, A.M.; MOURAD, D.M.; HAMED, A.A.; HAFEZ, O.R. Rumen fermentation and microbiota in Shami goats fed on condensed tannins or herbal mixture. **BMC Veterinary Research**, v.20, art.35, 2024. DOI: https://doi.org/10.1186/s12917-024-03887-2.

SAMAL, L.; CHAUDHARY, L.C.; AGARWAL, N.; KAMRA, D.N. Effect of plants containing secondary metabolites as feed additives on rumen fermentation and rumen microbial profile of buffaloes. **Animal Nutrition and Feed Technology**, v.15, p.427-437, 2015. DOI: https://doi.org/10.5958/0974-181X.2015.00043.8.

SANGKAEW, B.; VIENNASAY, B.; CHERDTHONG, A.; NORRAPOKE, T.; SUPAPONG, C. Effects of high protein yeast with oil palm frond on feed utilization and blood chemical of Boer crossbred goats. **Scientific Reports**, v.15, art.15438, 2025. DOI: https://doi.org/10.1038/s41598-025-99866-0.

SWARTZ, T.H.; BRADFORD, B.J.; MALYSHEVA, O.; CAUDILL, M.A.; MAMEDOVA, L.K.; ESTES, K.A. Effects of dietary rumen-protected choline supplementation on colostrum yields, quality, and choline metabolites from dairy cattle. **JDS Communications**, v.3, p.296-300, 2022. DOI: https://doi.org/10.3168/jdsc.2021-0192.

VAN SOEST, P.V.; ROBERTSON, J.B.; LEWIS, B.A. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. **Journal of Dairy Science**, v.74, p.3583-3597, 1991. DOI: https://doi.org/10.3168/JDS.S0022-0302(91)78551-2.

WANG, J.; ZHAO, G.; ZHUANG, Y.; CHAI, J.; ZHANG, N. Yeast (*Saccharomyces cerevisiae*) culture promotes the performance of fattening sheep by enhancing nutrients digestibility and rumen development. **Fermentation**, v.8, art.719, 2022. DOI: https://doi.org/10.3390/fermentation8120719.

WANG, L. Advances in nutritional manipulation of rumen fermentation. **Animals**, v.15, art.833, 2025. DOI: https://doi.org/10.3390/ani15060833.

YIN, X.; JI, S.; DUAN, C.; TIAN, P.; JU, S.; YAN, H.; ZHANG, Y.; LIU, Y. Age-related changes in the ruminal microbiota and their relationship with rumen fermentation in lambs. **Frontiers in Microbiology**, v.12, art.679135, 2021. DOI: https://doi.org/10.3389/fmicb.2021.679135.

ZHANG, Y.; USMAN, S.; LI, Q.; LI, F.; ZHANG, X.; NUSSIO, L.G.; GUO, X. Effects of antioxidant-rich *Lactiplantibacillus plantarum* inoculated alfalfa silage on rumen fermentation, antioxidant and immunity status, and mammary gland gene expression in dairy goats. **Journal of Animal Science and Biotechnology**, v.15, art.9, 2024. DOI: https://doi.org/10.1186/s40104-023-00977-3.

ZHAO, W.; ABDELSATTAR, M.M.; WANG, X.; ZHANG, N.; CHAI, J. *In vitro* modulation of rumen fermentation by microbiota from the recombination of rumen fluid and solid phases. **Microbiology Spectrum**, v.11, e03387-22, 2023. DOI: https://doi.org/10.1128/spectrum.03387-22.

ZHU, W.; WEI, Z.; XU, N.; YANG, F.; YOON, I.; CHUNG, Y.; LIU, J.; WANG, J. Effects of *Saccharomyces cerevisiae* fermentation products on performance and rumen fermentation and microbiota in dairy cows fed a diet containing low quality forage. **Journal of Animal Science and Biotechnology**, v.8, art.36, 2017. DOI: https://doi.org/10.1186/s40104-017-0167-3.

Author contributions

Rezki Amalyadi: conceptualization, investigation, methodology, writing – original draft, writing – review & editing.

Chief editor: Edemar Corazza
Edited by: Madalena Rinaldi

Data availability statement

Data in article: research data are available in the published article.

Declaration of use of AI technologies

During the preparation of this work, the author(s) used ChatGPT (OpenAI) and Grammarly solely to assist with grammar checking, language editing, and improving the clarity of the manuscript. After this use, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the final content of the manuscript.

Conflict of interest statement

The authors declare no conflicts of interest.

Disclaimer/Publisher's note

The statements, opinions, and data contained in all texts published in Pesquisa Agropecuária Brasileira (PAB) are solely those of the individual author(s) and not of the journal's publisher, editor, and editorial team, who disclaim responsibility for any injury to people or property resulting from any referred ideas, methods, instructions, or products.

The mention of specific chemical products, machines, and commercial equipment in the texts published in this journal does not imply their recommendation by the publisher.