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NUTRIENT DIGESTIBILITY, RUMEN FERMENTATION AND NITROGEN UTILIZATION OF YANKASSA RAMS SUPPLEMENTED MILNE-RECH (*Piliostigma thonningii* Schum) ESSENTIAL OIL-BASED DIET

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Abstract. This study investigated the impact of *Piliostigma thonningii* Schum. essential oil (PTS) supplementation on nutrient digestibility, nitrogen metabolism and ruminal fermentation characteristics in growing rams. Twenty-one clinically healthy Yankassa ram lambs (average initial weight: 10.55 ± 0.60 kg) were randomly allocated into three dietary treatments (n = 7 per group) in a completely randomized design. The experimental period lasted for 90 days. Treatment groups included a control (T1) receiving the basal diet alone, while T2 and T3 were supplemented with 5 mL/kg and 10 mL/kg diet of PTS, respectively. Digestibility of dry matter (DM), crude protein (CP), ether extract (EE), crude fiber (CF), nitrogen-free extract (NFE), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL) and cellulose was significantly higher ($P < 0.05$) in T3 compared to the control, indicating enhanced nutrient utilization with higher PTS inclusion. Ash and hemicellulose digestibility were significantly greater ($P < 0.05$) in T2 than T3, though both outperformed the control group ($P < 0.05$). Nitrogen intake, fecal nitrogen output, total nitrogen loss and percentage nitrogen utilization showed significant improvement ($P < 0.05$) in PTS-supplemented groups, with T3 recording the highest values. Urinary nitrogen and nitrogen retention were notably elevated in T2, while T3 showed intermediate values, both significantly higher than the control ($P < 0.05$). Rumen fermentation parameters demonstrated significant modulation by PTS. Supplemented groups recorded lower ($P < 0.05$) rumen pH, ammonia nitrogen, methane emissions, acetic acid concentration and acetate-to-propionate ratio. Conversely, total volatile fatty acids (TVFA), iso-butyric, iso-valeric and valeric acid levels were significantly increased ($P < 0.05$) in T2 and T3. Butyric and propionic acid concentrations peaked in T3 ($P < 0.05$), indicating improved fermentation efficiency. In conclusion, dietary inclusion of *Piliostigma thonningii* essential oil notably enhanced nutrient digestibility, nitrogen retention and ruminal fermentation efficiency in growing rams. The 10 mL/kg diet supplementation level was found to be the most effective in optimizing performance and promoting overall animal well-being.

Keywords: *Small ruminants, sheep, tropical phytogenic, essential oils, nutrient utilization, ruminal fermentation characteristics.*

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1. Introduction

Sheep production in tropical regions, particularly under smallholder farming systems, continues to face a multitude of challenges, including poor feed efficiency, low productivity and the widespread misuse of synthetic antibiotics as growth enhancers (Anaso & Olafadehan, 2025). These practices have not only compromised animal performance but have also raised serious concerns about the safety and quality of meat products intended for human consumption.

In the last decade, there has been growing interest in the application of essential oils (EOs) - aromatic, bioactive plant extracts - in animal nutrition and health management (Kholif *et al*., 2018; Alabi *et al*., 2024; Ike *et al*., 2024). These compounds, rich in polyphenolics and other secondary metabolites, have demonstrated promising abilities to modulate rumen fermentation, enhance nutrient absorption and support overall physiological function in ruminant animals (Kholif *et al*., 2012, 2018).

To mitigate the adverse effects of antibiotic misuse and promote sustainable animal production, the use of phytogenic feed additives - especially essential oils - has emerged as a viable alternative (Anaso *et al*., 2024a, 2024b, 2024c, 2024d; Anaso & Alagbe, 2025). According to Anaso (2023a, 2023b), essential oils are volatile aromatic substances derived from various parts of plants, including flowers, buds, leaves, twigs, bark, roots and fruits. They are typically obtained via steam distillation or organic solvent extraction, methods that preserve their bioactive potency and aromatic characteristics.

Essential oils are complex mixtures comprising terpenes, alcohols, aldehydes, ketones, esters, phenols and acids, among others (Negi, 2012; Anaso, 2023b; Anaso *et al*., 2024b). These compounds are known for their antimicrobial, antifungal, antioxidant, insecticidal and preservative properties. Traditionally, EOs have been used for centuries across different cultures for medicinal and preservative purposes (Anaso, 2025a,b,c; Anaso *et al*., 2025a).

In animal production, EO supplementation has shown beneficial effects on feed utilization, immune response and overall performance, particularly in rabbits (Celia *et al*., 2016; Anaso *et al*., 2025b). One promising yet underexplored plant in this regard is *Piliostigma thonningii* Schum. - commonly referred to as Camel's Foot or Monkey Bread. A small, gnarled tree belonging to the Caesalpiniaceae family and widespread across African savannahs, *P. thonningii* features dark brown to black fissured bark and has a long history in ethnoveterinary medicine for treating conditions like dermatosis and malaria (Anaso *et al*., 2024b; Anaso, 2023b).

Preliminary studies have revealed that *P. thonningii* essential oil (PTEO) possesses potent antioxidant, antibacterial and insecticidal properties. However, despite the growing body of research on phytogenics in livestock nutrition, there remains a dearth of information on the effects of *P. thonningii* EO on key performance metrics - particularly in ruminants such as sheep. Prior research by Anaso et al. (2023; 2025c, 2025d,e,f) has demonstrated encouraging outcomes in terms of growth performance and nutrient digestibility, but further studies are needed to fully understand its functional potential.

Moreover, the variable outcomes reported in EO-based supplementation studies highlight the influence of several factors, including the chemical composition of the oil, animal species, environmental conditions and overall diet composition (Omonijo *et al*., 2018). Only a limited number of studies have assessed essential oils with clearly defined chemical profiles for their effects on the rumen microbiome and fermentation dynamics.

Given these gaps in knowledge, the present study was designed to evaluate the influence of *Piliostigma thonningii* seed essential oil (PTS EO) on key physiological and metabolic parameters in growing rams. Specifically, the objectives of this research were to:

1. Assess the effects of PTS EO on nutrient digestibility in rams.
2. Evaluate changes in ruminal fermentation characteristics following PTS EO supplementation.

3. Determine nitrogen utilization patterns in rams fed diets supplemented with PTS EO.

2. Materials and methods

2.1. Collection of Milne-Rech (PTS) seeds and extraction of the essential oil

Seeds of *Piliostigma thonningii* (Milne-Rech) were obtained from the Federal Capital Territory, Nigeria, situated within the southern Guinea savannah agro-ecological zone. After harvesting, the seeds were air-dried in a shaded environment to maintain their phytochemical composition. Once adequately dried, the seeds were ground into a fine powder and kept at ambient room temperature in preparation for essential oil extraction.

For the extraction process, precisely 100 grams of the powdered seeds were subjected to steam distillation. The ground material was combined with 700 mL of distilled water and heated to 100 °C for three hours using a stainless-steel distillation apparatus equipped with a condenser. This setup facilitated the vaporization of volatile compounds, which were subsequently cooled and condensed into liquid form. The essential oil was collected as droplets using a Clevenger-type apparatus, following the methodology outlined by Anaso (2023b) and Anaso and Alagbe (2025).

2.2. Experimental site

The experimental study was conducted at the Co-farms Green Aid Revolution and Morugo Farms research station, located within the geographic coordinates of 08°51' to 09°37' N latitude and 07°20' to 07°51' E longitude. The site receives an average annual rainfall ranging from 1,145 mm to 1,631 mm. Climatic conditions vary seasonally, with wet season temperatures ranging from 25.8 °C to 30.2 °C, while dry season temperatures rise significantly, reaching between 36 °C and 42 °C. According to Anaso (2025), relative humidity averages around 60% during the rainy season and declines to approximately 30% in the dry season.

2.3. Experimental animals, management and diets

A total of twenty-one healthy Yankassa ram lambs, aged between 6 and 7 months and averaging 10.55 ± 0.60 kg in initial body weight, were selected from a reputable livestock market in northern Nigeria for the study. Upon arrival at the experimental site, the animals were individually housed in pens measuring 1.3 m^2 each, arranged within a larger corral enclosure of 7 × 9 × 5 meters. Prior to the animals' arrival, the housing facilities were thoroughly sanitized two weeks in advance using Morigad® - a broad-spectrum antibiotic disinfectant - and Hypo®, a sodium hypochlorite solution composed of caustic soda and demineralized water, to ensure optimal hygiene and biosecurity.

During a mandatory two-week quarantine and acclimatization period, all lambs underwent a comprehensive preventive health protocol. This included a subcutaneous injection of Avomec® (0.5 mL per 25 kg body weight) to control internal and external parasites and an intramuscular injection of long-acting oxytetracycline (1 mL per 10 kg body weight) to prevent bacterial infections. To reduce the physiological stress associated with handling and relocation, each lamb was administered an oral dose of Vitalyte®. Additionally, all animals were vaccinated against peste des petits ruminants (PPR) via subcutaneous injection of 1 mL of a live attenuated vaccine containing 10^2.5 $TCID_{50}$ of the virus.

The feeding trial lasted for 90 days and was conducted in alignment with the nutrient requirements for growing sheep as recommended by the National Research Council (NRC, 2007). The composition of the experimental diets is outlined in Table 1. Throughout the 12-week study period (February to April), feed was provided at a rate of 5% of each animal's body weight on a dry matter basis, with weekly adjustments made in response to changes in body weight. Feeding was done twice daily, at 8:00 a.m. and 4:00 p.m., with continuous access to clean drinking water. Feed allocation was carefully managed to minimize waste and ensure accurate intake measurement.

The animals were randomly distributed into three dietary treatment groups. Group T1 (control) received only the basal diet, while groups T2 and T3 were fed the basal diet supplemented with *Piliostigma thonningii* seed essential oil (PTS) at inclusion levels of 5 mL/kg and 10 mL/kg of feed, respectively.

Table 1. Ingredient and chemical composition of the experimental diets (% DM)

Ingredient	Quantity
Maize	25.00
Corn bran	15.00
Biodegraded sugarcane scrapings	15.00
Groundnut cake	17.00
Cowpea husk	25.00
Salt	0.50
Limestone	2.00
Premix	0.50
Total	100.00

2.4. Digestibility study

The measurement of conjugated bilirubin followed a method akin to that used for total bilirubin but utilized an accelerator-free reagent to selectively assess only the conjugated fraction.

After the completion of the 84-day feeding trial, a 14-day digestibility assessment was conducted. This phase included a 7-day adaptation period to the metabolic cages followed by 7 days dedicated to fecal and urine collection. Three rams from each dietary treatment group were selected, weighed and housed individually in specialized metabolic cages to facilitate separate collection of excreta.

Each animal was offered a measured quantity of feed and had unrestricted access to clean drinking water. During the collection phase, total feces produced daily by each ram were gathered and weighed. From the collected feces, a 10% subsample was taken, oven-dried at 65°C for 48 hours and preserved for subsequent chemical composition analysis.

Urine was simultaneously collected daily in plastic containers pre-treated with a few drops of 10% sulfuric acid (H_2SO_4) to minimize nitrogen loss through ammonia volatilization. The urine samples were then refrigerated and stored under controlled conditions until nitrogen balance determination could be performed.

The apparent digestibility coefficient (%) was determined using the following formula:

The apparent digestibility percentage was calculated using the formula: the difference between the amount of nutrient consumed and the amount excreted in the feces - determined as (% nutrient in feed × quantity of feed consumed) minus (% nutrient in feces × quantity of feces voided) - divided by the total nutrient consumed (% nutrient in feed × quantity of feed consumed) and then multiplied by 100.

This calculation estimates the proportion of a specific nutrient that was absorbed and utilized by the animal from the total amount ingested.

For nitrogen utilization, nitrogen retention was computed by subtracting the total amount of nitrogen lost in feces and urine from the total nitrogen intake. Subsequently, nitrogen utilization (%) was calculated as:

$$\text{Nitrogen Utilization (\%)} = (\text{Nitrogen retained} \div \text{Nitrogen intake}) \times 100.$$

2.5. Ruminal fermentation parameters

During the final day of each experimental week from the 6th to the 10th week, five animals were randomly selected from each dietary treatment group to obtain rumen fluid samples. Approximately 30 mL of rumen fluid was collected per animal using an esophageal probe, three hours after the morning feeding session. The pH of the rumen fluid was measured immediately on-site using a portable digital pH meter.

To separate feed particles, the rumen fluid was passed through four layers of gauze and the filtrate was divided into two portions for subsequent analyses:

- Tube 1 was used for protozoa enumeration and classification, following the method outlined by Onodera et al. (1977).
- Tube 2 was frozen at -20°C for later determination of ammonia nitrogen (NH_3–N) and volatile fatty acid (VFA) concentrations. Ammonia analysis followed the protocol by Preston (1995).

For VFA analysis, the frozen rumen fluid samples were thawed and a 1.6 mL aliquot was mixed with 0.4 mL of 25% metaphosphoric acid (in a 4:1 ratio) to precipitate proteins. The mixture was centrifuged at 15,000 rpm for 20 minutes at 4°C using a K1015 Micro Prime centrifuge (Centurion Scientific Ltd., UK). The resulting supernatant was used to quantify VFA concentrations through gas chromatography.

The VFA analysis was performed using a Thermo Fisher TRACE1300 gas chromatograph equipped with an AS3800 autosampler and a HP-FFAP capillary column (19091F-112; 25 m length, 0.32 mm outer diameter, 0.50 μm film thickness; Agilent Technologies, USA). Hydrogen gas served as the carrier at a flow rate of 1.35 mL/min while air, hydrogen (combustion) and nitrogen (make-up gas) were maintained at 450, 40 and 35 mL/min, respectively.

A 0.1 μL sample volume was injected in splitless mode, with a total H_2 flux of 31.35 mL/min (equivalent to 63.432 Pa). The injector and detector temperatures were held at 250°C and the oven temperature program was as follows:

- Initial hold at 80°C for 1 min
- Ramp to 120°C at 20°C/min and hold for 3 min
- Final increase to 205°C at 10°C/min and hold for 2 min. This yielded a total run time of 9 minutes.

Methane (CH_4) production was estimated using the formula described by Wolin (1960):

$$CH_4 = (\text{Acetic} + 2 \times \text{Propionic}) - \text{Fermentative } CO_2,$$

where fermentative CO_2 = (Acetic ÷ 2) + (Propionic ÷ 4) + (1.5 × Butyric acid).

2.6. Statistical analyses

Data pertaining to thermoregulatory responses, serum biochemistry, immune status, oxidative stress indicators and semen quality were statistically evaluated using analysis of variance (ANOVA) based on a completely randomized design. The analysis was conducted with SPSS software (version 23.0). Differences among treatment means were assessed using Duncan's multiple range test and statistical significance was determined at $P \leq 0.05$.

3. Results and discussion

3.1. Nutrient digestibility of rams fed Milne-Rech Seed essential oil supplemented diet

Table 2 displays the nutrient digestibility outcomes in rams fed diets supplemented with *Piliostigma thonningii* seed essential oil (PTS). Apparent digestibility values for dry matter (DM), crude protein (CP), ether extract (EE), crude fiber (CF), nitrogen-free extract (NFE), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL) and cellulose followed a consistent trend. The highest ($P < 0.05$) digestibility was recorded in rams receiving 10 mL/kg of PTS (T3), while the lowest values were observed in the control group (T1). Digestibility of ash and hemicellulose was significantly greater ($P < 0.05$) in T2 compared to T3; however, both were not significantly different ($P > 0.05$) from each other, though both outperformed the control.

The enhanced digestibility observed in this study aligns with the findings of Anaso et al. (2025b), who reported improved CP and CF utilization in growing livestock following *Piliostigma thonningii* seed essential oil supplementation, attributing this to increased bioavailability of protein for tissue deposition. Similar results have been reported by Patra et al. (2001), Shehata et al. (2003) and Hernandez et al. (2004), were garlic essential oil supplementation improved nutrient digestibility. The observed improvements in CP digestibility in the current study may be attributed to a rise in the population of beneficial gut microbes that enhance the synthesis of endogenous digestive enzymes, thereby improving nutrient breakdown and absorption, as well as feed intake efficiency (Anaso & Olafadehan, 2025; Anaso *et al*., 2025b).

Table 2. Nutrient digestibility of rams fed *Piliostigma thonningii* essential oil supplemented diet

Parameter (%)	T1	T2	T3	SEM
Dry matter digestibility	80.59^{c}	84.14^{b}	84.80^{a}	0.23
Crude protein digestibility	83.36^{c}	87.47^{b}	89.29^{a}	2.27
Ether extract digestibility	83.77^{c}	87.63^{b}	88.95^{a}	0.64
Ash	55.46^{b}	78.83^{a}	79.08^{a}	0.53
Crude fibre digestibility	60.59^{c}	73.95^{b}	78.34^{a}	0.35
Nitrogen free extract	84.30^{c}	85.88^{b}	86.91^{a}	0.73
Neutral detergent fibre	74.81^{c}	83.14^{b}	83.62^{a}	0.15
Acid detergent fibre	76.49^{c}	81.11^{b}	81.74^{a}	0.26
Acid detergent lignin	20.54^{c}	34.59^{b}	48.59^{a}	0.37
Hemicellulose	79.44^{b}	85.28^{b}	86.66^{a}	0.86
Cellulose	84.96^{c}	89.34^{b}	91.06^{a}	0.50

Note: Means with the different superscripts along the row are significantly ($P < 0.05$) different T1, 0 ml *P. thonningii* essential oil; T2, 5 ml *P. thonningii* essential oil; T3, 10 ml *P. thonningii* essential oil/kg diet

3.2. Nitrogen utilization of rams fed Milne-Rech Seed essential oil supplemented diet

Table 3 summarizes the nitrogen utilization metrics in rams fed diets supplemented with *Piliostigma thonningii* seed essential oil (PTS). Nitrogen intake, fecal nitrogen, total nitrogen output and percentage nitrogen utilization exhibited a similar pattern, with rams receiving 10 mL/kg diet PTS (T3) demonstrating significantly higher ($P < 0.05$) values than those in the control group, which recorded the lowest. Although urinary nitrogen excretion and nitrogen retention were significantly higher ($P < 0.05$) in T2 compared to T3, both treatments performed similarly ($P > 0.05$) and both outperformed the control group, which had the least values ($P < 0.05$).

The nitrogen intake recorded in this study aligns with the findings of Adelusi et al. (2016), who reported intake levels ranging from 7.75 to 10.16 g/day. These results also corroborate the findings of Anaso et al. (2025a), who observed that livestock diets enriched with essential oils led to improved nitrogen intake. Adelusi et al. (2016) further attributed enhanced nitrogen consumption in small ruminants to elevated protein intake resulting from improved feed palatability and digestibility.

The urinary and fecal nitrogen outputs recorded here were lower than those reported by Jiwuba (2020), but higher than the values (1.59-1.90 g/day in feces and 0.02-0.40 g/day in urine) documented by Ajagbe et al. (2019). Additionally, the total nitrogen output in this study was less than the 5.29-6.51 g/day reported by Abatan et al. (2015), suggesting more efficient nitrogen utilization by the experimental animals. The nitrogen utilization rates (83.10-90.70%) obtained in this research are in agreement with the values reported by Ajagbe et al. (2019), indicating a favorable nitrogen balance. According to Oni et al. (2010), such high nitrogen retention is typically indicative of reduced urinary nitrogen losses and improved nutrient digestibility, both of which are desirable outcomes in ruminant nutrition.

Table 3. Nitrogen utilization of rams fed *Piliostigma thonningii* essential oil supplemented diet

Parameter (%)	T1	T2	T3	SEM
Nitrogen intake	5.03^{c}	6.20^{b}	6.57^{a}	0.18
Faecal nitrogen	0.80^{c}	0.94^{b}	1.37^{a}	0.02
Urinary nitrogen	0.01^{b}	0.02^{a}	0.02^{a}	0.00
Total nitrogen output	0.80^{c}	0.92^{b}	1.32^{a}	0.00
Nitrogen retention	4.17^{b}	5.24^{a}	5.30^{a}	0.03
% nitrogen utilization	78.81^{c}	85.03^{b}	87.42^{a}	0.46

Note: Means with the different superscripts along the row are significantly ($P < 0.05$) different T1, 0 ml *P. thonningii* essential oil; T2, 5 ml *P. thonningii* essential oil; T3, 10 ml *P. thonningii* essential oil/kg diet

3.3. Rumen fermentation characteristics of rams fed Milne-Rech Seed essential oil supplemented diet

Table 4 provides detailed insights into the rumen fermentation responses of rams fed diets supplemented with Piliostigma thonningii seed essential oil (PTS). Significant reductions ($P < 0.05$) in ruminal pH, ammonia nitrogen (NH_3-N), methane concentration, acetic acid and acetate-to-propionate ratio were observed in the PTS-supplemented groups (T2 and T3) compared to the control (T1). Conversely, total volatile fatty acids (VFAs), iso-butyric, iso-valeric and valeric acid concentrations were significantly elevated ($P < 0.05$) in T2 and T3. Butyric and propionic acid levels peaked in T3 and were lowest in T1.

These fermentation parameters - total VFAs, acetic, butyric, propionic, iso-butyric, iso-valeric, valeric acids, NH_3-N and ruminal pH - are critical indicators of microbial activity in the rumen (Anaso *et al*., 2025b). Enhanced VFA concentrations and reduced NH_3-N levels in the PTS-supplemented groups suggest a modulation of microbial populations, possibly reducing proteolysis while promoting carbohydrate fermentation. The increase in VFAs - particularly propionic and butyric acids - implies improved energy supply and enterocyte development, which supports rumen health and overall animal performance. Butyric acid, in particular, is vital for epithelial integrity in the lower digestive tract (Butzner *et al*., 1994), while elevated iso-butyric acid may indicate enhanced proteolytic activity (Cardona *et al*., 2005).

The observed pH range (6.17-6.30) falls within the optimal range for fibrolytic microbial activity, confirming that PTS supplementation did not disrupt ruminal buffering capacity. This agrees with findings by Ryle and Ørskov (1990) and Van Soest (1994), who reported that ruminal pH is influenced by the balance of VFAs, ammonia, saliva and buffering compounds.

Methane reduction in the PTS groups aligns with studies by Cobellis et al. (2015) and Elazab et al. (2025), suggesting that essential oils can alter the methanogenic archaea or their metabolic pathways. The mechanism behind this reduction is attributed to the bioactive compounds in essential oils that directly suppress methanogens or shift fermentation pathways away from methane production (Ohene-Adjei *et al*., 2008; Wang *et al*., 2009; Hernandez *et al*., 2017). However, variable responses in methane output with different essential oils and dosages have been reported, with some studies showing no significant effects (Benchaar *et al*., 2007; Tomkins *et al*., 2015; Beauchemin & McGinn, 2006).

Overall, PTS supplementation significantly modulated rumen fermentation patterns, supporting enhanced nutrient utilization, reduced nitrogen losses and mitigated methane emissions - key indicators of improved rumen efficiency and environmental sustainability. These findings further emphasize the potential of PTS essential oil as a natural phytogenic additive in small ruminant nutrition.

Table 4. Rumen fermentation characteristics of rams fed *Piliostigma thonningii* essential oil supplemented diet

Parameter (%)	T1	T2	T3	SEM
pH	6.36^{a}	6.27^{ab}	6.22^{b}	0.03
Ammonia nitrogen	28.25^{a}	23.45^{b}	23.14^{b}	0.16
Methane	24.13^{a}	20.40^{b}	20.02^{b}	0.42
Total volatile fatty acids	88.90^{b}	90.33^{a}	91.31^{a}	0.47
Acetic acid	40.55^{a}	38.53^{b}	38.03^{b}	0.21
Propionic acid	22.45^{c}	26.16^{b}	26.80^{a}	0.25
Isobutyric acid	2.15^{b}	2.49^{a}	2.55^{a}	0.04
Butyric acid	15.48^{c}	17.13^{b}	17.71^{a}	0.16
Isovaleric acid	3.57^{b}	4.30^{a}	4.55^{a}	0.15
Valeric acid	2.95^{b}	3.02^{a}	3.05^{a}	0.02
Acetate propionate ratio	1.81^{a}	1.47^{b}	1.42^{b}	0.02

Note: Means with the different superscripts along the row are significantly ($P < 0.05$) different T1, 0 ml *P. thonningii* essential oil; T2, 5 ml *P. thonningii* essential oil; T3, 10 ml *P. thonningii* essential oil/kg diet

4. Conclusion

Based on the current findings, supplementation with *Piliostigma thonningii* seed essential oil (PTS) markedly enhanced nutrient digestibility, improved nitrogen utilization efficiency and positively influenced rumen fermentation dynamics in sheep. Notably, the supplementation level of 10 mL PTS per kg of diet proved more effective than 5 mL/kg, as evidenced by superior outcomes across several key parameters. This suggests that the higher inclusion level provides a more pronounced physiological benefit, making it the optimal dosage for maximizing digestive and fermentative efficiency in small ruminants under similar production conditions.

Declaration

Authors declare no conflicts of interest.

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