

Performance of West African dwarf does fed diets supplemented with *Piliostigma thonningii* and *Daniellia oliveri* essential oils: effects on immune function, oxidative stress markers, milk production, and rumen fermentation

Emmanuel U. Anaso ^{1*} and Donken I. Ajogi ²

*corresponding author: dranasouemmanuel@gmail.com

¹*Department of Animal Science, Faculty of Agriculture, Federal University of Agriculture Mubi, Adamawa Nigeria*

²*Department of Public Health, Faculty of Veterinary Medicine, University of Abuja, Abuja, Nigeria.*

ABSTRACT

This study explored the impact of *Daniellia oliveri* (DOV), *Piliostigma thonningii* seed oil (PTN), and their mixture (MEO; 1:1 v/v) on immunological response, oxidative stress biomarkers, rumen fermentation, milk production in West African dwarf does. In a 50-day study, 28 healthy does weighing 33.73 ± 0.40 kg were randomly assigned to the control and three additional dietary groups (n = 7). Treatments included a basal diet alone (T1), basal diet + 10 ml/kg PTN (T2), basal diet + 10 ml/kg DOV (T3), and basal diet + 10 ml/kg MEO (T4). Milk production (yield) and composition were enhanced ($P < 0.05$) in groups (T2-T4) compared with the control, with T4 showing the greatest enhancement. Immunoglobulins (IgG, IgA, IgM), triiodothyronine (T3), superoxide dismutase, catalase, total antioxidant capacity, glutathione peroxidase and reductase and increased markedly ($P < 0.05$) in supplemented groups, while malondialdehyde and cortisol levels were highest in the control group. Rumen fermentation profiles also improved, with reduced pH, ammonia nitrogen, methane, acetic acid, and acetate-to-propionate ratio, alongside higher concentrations of volatile fatty acids. In conclusion, PTN, DOV, and particularly their mixture enhanced milk yield and quality, immune competence, antioxidant defense, and rumen efficiency.

Keywords: *Piliostigma thonningii*; *Daniella oliveri*; phytogetic feed additives; dairy goats; oxidative stress; rumen fermentation

INTRODUCTION

The prohibition of sub-therapeutic antimicrobial use in ruminant production has created an urgent need for cost-effective alternatives that sustain productivity without compromising product quality. Among these alternatives are plant nutraceuticals/phytogenics, probiotics, prebiotics, and vaccines, which have demonstrated potential in livestock enhancement (Anaso and Anaso, 2025; Anaso et al., 2025a). Essential oils, volatile compounds obtained mainly through distillation, have attracted attention due to their ability to modulate rumen fermentation, harmful emissions, and livestock enhancement (Zeng et al., 2015; Anaso, 2026a,b).

Although past researches have reported beneficial effects of essential oils (EO) supplementation on rumen characteristics, milk yield, and fatty acid profiles, findings remain inconsistent. Differences in chemical composition, diet, animal species, and environmental conditions contribute to these variable outcomes (Omonijo et al., 2018). Chemically, phytogenics are complex mixtures of terpenes, alcohols, aldehydes, ketones, esters, phenols, and acids, conferring antimicrobial, antioxidant, antifungal, and preservative properties (Negi, 2012; Anaso, 2023b; Anaso et al., 2024a). Traditionally used in medicine and food preservation, their application in animal nutrition has shown improvements in feed adaptability, digestibility, immunity, and overall livestock and livestock byproduct productivity (Celia et al., 2016; Anaso et al., 2024c).

Two promising yet underexplored African plants are *Piliostigma thonningii* and *Daniellia oliveri* (West African copal tree). *P. thonningii* is widely distributed across African savannahs and has long-standing ethnoveterinary uses, while preliminary findings indicate its essential oil possesses antioxidant, antibacterial, and insecticidal activities (Anaso et al., 2023; 2025c). Similarly, *D. oliveri* contains vitamins, minerals, amino acids, and diverse phytochemicals such as alkaloids, flavonoids, polyphenols, and sapogenin, which confer anti-inflammatory, antimicrobial, and antistress functions (Adubiario et al., 2016; Anaso, 2025a-e; Anaso et al., 2025a-g; Anaso, 2026a,b). Despite this potential, evidence on their nutritional efficacy, particularly in lactating ruminants, remains scarce.

To address this gap, the present research/study was designed to:

1. Elucidate the effects of *P. thonningii*, *D. oliveri*, and their mixture on milk production in West African Dwarf does.
2. Assess immune and oxidative stress responses to dietary supplementation.
3. Examine changes in ruminal fermentation characteristics under these treatments.

MATERIALS AND METHODS

Collection and extraction of Milne-Rech and Daniella Oliveri seeds

The agro-ecological zone of southern Guinea savannah in Nigeria is where Milne-Rech (PTN) seeds were acquired. The seeds were shade-dried, ground into a fine powder, and kept at room temperature until the essential oil was extracted in order to maintain their bioactive integrity (Anaso et al., 2024d). A stainless-steel distillation apparatus with a condenser was used to steam-distill 120 g of seed powder with 1000 ml of distilled water for three hours at 100 °C. Using a Clevenger-type device, volatile fractions were collected as droplets in accordance with Anaso (2023a) and Anaso & Alagbe (2025a-c) protocols.

Fresh, mature leaves of *Daniellia oliveri* were harvested from naturally occurring stands in the Federal Capital Territory, Nigeria. The leaves, characterized by glossy dark-green surfaces with lighter mid-veins and undersides, were taxonomically authenticated by a specialist at the Forestry Research Institute of Nigeria. The leaves were air-dried to constant weight and ground into a fine powder after being thoroughly cleaned with running and distilled water to get rid of any remaining material. 250 grams of powdered leaf material were macerated in 1000 milliliters of 80% ethanol (BDH) for 48 hours in an airtight container in order to extract the substance. After passing through Whatman No. 1 filter paper, the extract was kept at 4 °C for further examination Anaso (2025a,b).

Site of experimentation

The Co-farms Green Aid Revolution and Morugo Farms research site, which is situated between 08°51' and 09°37' N latitude and 07°20' and 07°51' E longitude, was the site of the experimental investigation. Rainfall in the region averages between 1,145 and 1,631 mm per year. Seasonal variations in temperature are observed, with highs of between 36°C and 42°C during the dry season and between 25.8°C and 30.2°C during the rainy season (Anaso et al., 2024b). The average relative humidity is over 60.0% during the wet season and drops to almost 30.0% during the dry months, according to Anaso (2025b) and (Anaso & Salihu, 2025).

Management, nutrition, and experimental animals

In a fully randomized design, twenty-eight clinically healthy West African Dwarf (WAD) does weighing similar amounts at baseline (33.73 ± 0.40 kg) were divided into four groups of seven animals each and randomly assigned to four different nutritional treatments. Within a larger corral facility ($10 \times 15 \times 8$ m), each doe was kept separately in a regular enclosure (1.9 m^2). To guarantee stringent hygienic and biosecurity conditions, every pen was meticulously cleaned and disinfected before the testing. The 50-day feeding

trial adhered to the National Research Council's suggested dietary requirements for nursing goats (NRC, 2007).

Table 1. Bioactive compounds of *Piliostigma thonningii* essential oil detected by the gas chromatography-mass spectrometry

Compounds	Percentage area	Mass peak
Azulene	0.42	25, 40, 42, 57
Beta myrcene	6.05	25, 72, 102, 106, 110
Beta limonene	17.85	25, 41, 43, 57
Cis- linaloxide	0.21	25, 39, 47, 49, 55
Alpha cymene	0.15	25, 44, 48
Beta ocimene	0.06	25, 88, 106
Trans beta ocimene	0.30	25, 39, 66, 70
4-methylpropiohenone	0.12	25, 88, 106, 109
1,3 dimethyl-4-Isoprophylbenze	3.11	25, 48, 51, 58, 69
Dodecane	0.19	25, 41, 43
Tridecane	1.20	60, 68, 77, 103
2,3-dimethylnephthalene	0.71	25, 44, 68, 92
1,8-dimethylnephthalene	0.22	25, 81, 87, 102, 117
Alpha thujene	0.19	25, 29, 38, 44
Beta pinene	25.02	25, 62, 68, 100
Terpinen-4-ol	2.60	25, 42, 47, 58
Alpha terpineol	3.70	25, 88, 93, 106
Gamma terpineol	5.11	25, 71, 79, 100
Alpha cubebene	2.09	25, 63, 69
Alpha yiangene	1.02	25, 41, 55, 108, 127
Alpha selinene	1.10	25, 40, 48, 51
Chrysathenine	0.08	25, 47, 57, 63
Alpha allyltoluene	0.29	25, 39, 47, 58
Borneol	1.44	25, 33, 39
Hexenyl acetate	2.83	25, 28, 37, 108
Camhene	1.50	25, 63, 68, 101
n-Nonanol	0.04	25, 69, 104
Trans-pinocarveol	0.62	25, 27, 29, 41, 55, 67
Cis pinocarveol	1.77	25, 41, 55, 67, 81, 10
Fenchol	0.96	25, 41, 58, 138
Alpha murolene	9.63	25, 39, 51, 105, 109

Reference; Anaso et al. (2024d)

Table 2. Bioactive compounds of *Daniellia oliveri* essential oil detected by the gas chromatography-mass spectrometry

Compound	Relative Abundance (%)
α -Pinene	18.40
β -Pinene	12.70
Limonene	9.60
Sabinene	7.30
Myrcene	6.50
Terpinen-4-ol	5.80
α -Terpineol	4.90
β -Caryophyllene	8.10
Germacrene D	6.20
Caryophyllene oxide	3.40

Reference; Anaso (2025)

Table 3 displays the experimental diets' makeup. In order to preserve precision in the nutritional supply, diets were provided on a dry matter basis and were adjusted weekly based on changes in each person's body weight.

Table 3. Composition of the experimental diet's ingredients (% DM)

Ingredient	Quantity
Yellow Corn	25.00
Corn zest	15.00
Fermented sugarcane peels	15.00
Peanut cake	17.00
Cowpea haulm	25.00
Common salt	0.50
Calcium carbonate	2.00
Commercial premix	0.50
Sum total	100.00
Chemical composition	Percentage
Dry matter (%) In % DM	93.10
Crude protein	15.70
Ether extract	5.78
Crude fibre	12.82
Crude ash	6.24
Organic matter	93.76
NFC	33.59
NDF	38.69
ADF	20.95
Lignin	2.89
Cellulose	18.06
Hemicellulose	17.74

Clean drinking water was accessible at all times, and food was given twice a day at 8:00 and 16:00. The following were the dietary interventions: In

Treatment 1, the control group was given only the basic diet; in Treatment 2, the basal diet was supplemented with 10 milliliters per kilogram of PTN; in Treatment 3, the basal diet was supplemented with 10 milliliters per kilogram of DOV; and in Treatment 4, the basal diet was supplemented with 10 milliliters per kilogram of a PTN–DOV mixture (MEO). Throughout the trial, feed intake was continuously tracked to reduce variability and guarantee dietary accuracy.

Blood sample extraction and analysis

Blood samples were taken from every goat (Doe) in each treatment group on the last day of the feeding trial. Jugular venipuncture was used to take a sample early in the morning before feeding or watering. Each Doe had around 5 mL of blood extracted into sterile vacuum tubes, which were then promptly put on ice and brought to the lab for examination. A chilled centrifuge (NOP-350R, NOP Medical Instruments, Punjabi, India) kept at 4 °C was used to centrifuge the samples for 15 minutes at 3,000 rpm in order to separate the plasma. To guarantee the accuracy of the data, plasma aliquots were processed and examined within four hours of collection. Using Stanbio-specific ELISA kits using the methods of Elghalid et al. (2020) and Anaso et al. (2025a), immunoglobulin classes (IgA, IgG, and IgM) were quantified in order to evaluate immune function. Triiodothyronine (T3), total antioxidant capacity (TAC), malondialdehyde (MDA), superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), glutathione reductase (GR), and cortisol were among the metabolic and oxidative stress indicators. These were measured in accordance with manufacturer protocols utilizing defined methodologies with commercial diagnostic kits.

Milk Output and analysis (yield and composition)

Three times a day, at 5am, 11am and 7pm, does were machine-milked, and each animal's daily milk yield was noted. Biweekly composite milk samples were taken during the study periods. To stop microbial growth and biochemical changes, samples were well mixed as soon as they were collected, and aliquots were stored in potassium dichromate. The preserved samples were brought to the lab in a refrigerated environment after being kept at 4 °C. Using an infrared milk analyzer (Milko Tester, Instruments Inc., Bulgaria), analyses of milk compositions were completed within 48 hours while adhering to conventional operating procedures.

Ruminal fermentation parameters

Between the third and fifth weeks of the trial, rumen fluid samples were taken. Four does were chosen at random from each treatment group on the last day of each week, and three hours after morning feeding, an esophageal probe was used to collect about 10 mL of rumen fluid. A portable

commercial digital pH meter was used to measure the ruminal pH on-site as soon as it was collected. After removing feed particles with four layers of sterile gauze, the rumen fluid was separated into two aliquots.

The first aliquot was used for protozoa classification and enumeration following the method of Onodera et al. (1977) and Anaso and Alagbe (2025c). The second aliquot was stored at -20°C for subsequent determination of ammonia nitrogen according to Preston (1995) and quantification of individual VFAs. For VFA analysis, samples were thawed at room temperature, and 1.6 mL of rumen fluid was mixed with 0.4 mL of 25% metaphosphoric acid. The mixture was centrifuged at 15,000 rpm for 20 min at 4°C while resulting supernatant was analyzed using a gas chromatograph equipped with an autosampler and a capillary column.

The carrier gas, hydrogen, was used at a rate of 1.35 mL/min. The temperatures of the injector and the flame ionization detector were kept at 250°C . The oven was set to hold at 80 degrees Celsius for one minute, ramp up to 120 degrees Celsius at 20 degrees Celsius per minute and hold for three minutes, then ramp up to about 205 degrees Celsius at 10 degrees Celsius per minute and hold for two minutes.

It took about nine minutes to complete the analysis run.

Wolin's (1960) stoichiometric equation was used as stated;
Fermentative carbon dioxide (CO_2) was calculated as:

$$\text{Fermentative CO}_2 = \left(\frac{\text{Propionate}}{4} \right) + \left(\frac{\text{Acetate}}{2} \right) + (1.5 \times \text{Butyrate})$$

Where:

- Acetate = ethanoic acid (C2)
- Propionate = methylacetic acid (C3)
- Butyrate = butanoic acid (C4)

Methane production was calculated as:

$$\text{CH}_4 = (\text{Acetate} + 2 \times \text{Propionate}) - \text{Fermentative CO}_2$$

Substituting the fermentative CO_2 equation:

$$\text{CH}_4 = (\text{Acetate} + 2 \times \text{Propionate}) - \left[\left(\frac{\text{Propionate}}{4} \right) + \left(\frac{\text{Acetate}}{2} \right) + (1.5 \times \text{Butyrate}) \right]$$

Therefore,

$$\text{CH}_4 = (\text{C2} + 2\text{C3}) - [(C3/4) + (C2/2) + (1.5C4)]$$

Statistical Analysis

A one-way analysis of variance was performed on all obtained data in accordance with the guidelines of a completely randomized design. Software

called SPSS, version 23.0 was used to perform statistical analyses. When treatment effects were deemed substantial, Duncan's multiple range test was used to determine group differences through mean separation. At $P < 0.05$, statistical significance was established.

RESULTS AND DISCUSSION

Milk output and quality of WAD does that are fed a diet enriched with essential oils of Danielella oliveri and Piliostigma thonningii

The milk yield and quality of WAD does given a diet supplemented with essential oils of *Danielella oliveri* and *Piliostigma thonningii* are displayed in Table 4. Doses supplemented with *Piliostigma thonningii* (PTN), *Daniellia oliveri* (DOV), and their mixture (MEO) (T2, T3, and T4) showed significantly higher milk output, protein, lactose, and solids-not-fat ($P < 0.05$) than the control group (T1). However, there were no discernible variations ($P > 0.05$) in the amount of lactose and solids-not-fat between T1 and T3. Although the degree of reaction varied by treatment, our results show that essential oil supplementation had a positive impact on milk yield and quality.

The improvement in lactational performance seen in all supplemented groups is in line with previous findings that essential oils can influence ruminant milk production; the results primarily depend on the chemical profile, dosage, and botanical source of the oil (Kholif et al., 2012; Kholif and Olafadehan, 2021).

Table 4. The milk output and quality of WAD does that are fed a diet enriched with essential oils of *Danielella oliveri* and *Piliostigma thonningii*

Parameter	T1	T2	T3	T4	SEM
Dry matter intake (g/day)	398.75 ^d	463.94 ^b	446.08 ^c	493.94 ^a	6.39
Milk yield (g/d.)	240 ^d	350 ^b	310 ^c	490 ^a	0.20
Milk fat (kg/d)	0.009 ^c	0.014 ^a	0.013 ^b	0.020 ^a	0.02
Milk protein (kg/d)	0.008 ^d	0.012 ^b	0.011 ^c	0.017 ^a	0.01
Solid not fat (kg/d)	0.022 ^c	0.032 ^b	0.029 ^c	0.045 ^a	0.03
Milk lactose (kg/d)	0.011 ^c	0.015 ^b	0.014 ^{bc}	0.022 ^a	0.03

The potential of PTN, DOV, and their combination to increase feed utilization efficiency, improve nutrient and energy availability, and regulate ruminal microbial activity may be the reason for the increased output. In particular, these oils probably maximize rumen fermentation and nutrient partitioning in favor of milk synthesis by encouraging the establishment of advantageous microbial communities while inhibiting undesired ones (Cobellis et al., 2016; Kholif et al., 2018; Elcoso et al., 2019).

*Immune and oxidative stress adaptations in WAD dogs given a diet enriched with essential oils of *Danielella oliveri* and *Piliostigma thonningii**

The oxidative stress and immunological parameters of WAD rats fed diets supplemented with essential oils of PTN, DOV, and MEO are shown in Table 5. IgG, IgA, IgM, T3 and SOD all showed significant increases ($P < 0.05$), with levels showing a continuous trend: lowest in T1 and highest in T4. Similarly, T2–T4 had significantly greater levels of catalase, GR, GPx and TAC than T1 ($P < 0.05$). In contrast, there were no significant differences between T2 and T4 ($P > 0.05$), although the amounts of MDA and cortisol, which are indicators of lipid peroxidation and physiological stress, respectively, were significantly greater in T1 but suppressed in the supplemented groups.

Table 5. Immune and oxidative stress adaptations in WAD dogs given a diet enriched with essential oils of *Danielella oliveri* and *Piliostigma thonningii*

Parameter	T1	T2	T3	T4	SEM
Immunoglobulin G (mg/100ml)	3416.80 ^d	5567.96 ^b	4877.80 ^c	6798.15 ^a	52.01
Immunoglobulin A (mg/ml)	0.24 ^c	0.33 ^{ab}	0.30 ^{bc}	0.40 ^a	0.02
Immunoglobulin M (mg/ml)	3.30 ^d	4.72 ^b	4.04 ^c	5.63 ^a	0.02
Triiodothyroxine (nmol/L)	1.53 ^c	4.47 ^b	4.09 ^b	6.00 ^a	0.54
Melanodialdehyde (nmol/L)	1.08 ^a	0.44 ^c	0.53 ^b	0.30 ^d	0.03
Superoxide dismutase (nmol/mL)	847.14 ^d	1170.89 ^b	1003.37 ^c	1700.28 ^a	18.56
Catalase (U/gHb)	1517.24 ^d	2008.12 ^b	1863.67 ^c	2553.39 ^a	37.21
Glutathione peroxidase (U/gHb)	176.45 ^c	204.00 ^b	196.19 ^b	255.47 ^a	3.73
Cortisol (ng/ml)	14.96 ^a	7.62 ^c	8.82 ^b	5.67 ^d	0.50
Total antioxidant capacity (nmol)	1.13 ^d	1.91 ^b	1.60 ^c	2.62 ^a	0.22
Glutathionereductase (IU/10 ¹¹ RBC)	1.20 ^d	1.95 ^b	1.57 ^c	2.49 ^a	0.07

The elevated levels of immunoglobulins, particularly IgG, IgM, and IgA, highlight enhanced humoral immune function, as these molecules constitute the first line of adaptive defense by binding pathogens, neutralizing toxins, and preventing microbial adhesion (Anaso et al., 2025a; Anaso, 2025b). Their increase under PTN, DOV, and especially MEO supplementation suggests immunomodulatory effects mediated by antioxidative bioactive compounds, consistent with earlier findings (Anaso et al., 2025d).

Enhanced T3 levels indicate improved thyroid activity and systemic metabolic function, reflecting better thermoregulation, growth, and energy metabolism in supplemented dogs (Anaso et al., 2025d; Bowen, 2010).

Similarly, reduced MDA concentrations confirm diminished oxidative stress, likely due to the radical-scavenging potential of phenolic compounds such as catechins, ketones, and volatile oils (El-Gogary et al., 2018). These effects are supported by bioactive phytochemicals including oleic acid, limonene, α -pinene, and β -caryophyllene, known for antioxidant, anti-inflammatory, and cortisol-lowering properties (Howhn & Marieb, 2010; Anaso, 2025a; Anaso et al., 2025d).

SOD activity was significantly upregulated in all supplemented groups, underscoring strengthened antioxidant defenses through the dismutation of superoxide radicals into less reactive species. This finding aligns with previous reports on essential oil supplementation (Lin et al., 2003; Anaso et al., 2025a–c). Complementarily, increased GPx and GR activities suggest enhanced glutathione-mediated defense, vital for protecting lipids, proteins, and nucleic acids from oxidative injury (Alagawany et al., 2015).

Finally, catalase, GPx, and GR activities were most pronounced in the MEO group, reinforcing the synergistic antioxidant potential of the PTN–DOV blend. These enzymes are critical in neutralizing hydrogen peroxide and maintaining redox homeostasis, thereby reducing cellular oxidative burden (Chelikani et al., 2004; Deponte, 2013; Anaso, 2023a, b).

*Fermentation properties of WAD rumen when presented with a diet supplemented with essential oils of *Danielella oliveri* and *Piliostigma thonningii**

The rumen fermentation profiles of WAD does fed diets supplemented with *Daniellia oliveri* (DOV), *Piliostigma thonningii* (PTN), and their mixture (MEO) are compiled in Table 6.

Table 6. Fermentation properties of WAD rumen when presented with a diet supplemented with essential oils of *Danielella oliveri* and *Piliostigma thonningii*

Parameter (%)	T1	T2	T3	T4	SEM
pH	6.29 ^a	6.23 ^b	6.28 ^a	6.23 ^b	0.02
Ammonia nitrogen	27.44 ^a	22.55 ^c	24.17 ^b	21.66 ^c	0.34
Methane	25.44 ^a	21.48 ^c	22.66 ^b	20.02 ^d	0.38
Total volatile fatty acids	78.23 ^c	88.67 ^a	82.62 ^b	89.98 ^a	0.60
Acetic/ethanoic acid	38.95 ^a	34.53 ^c	36.83 ^b	30.98 ^d	0.51
Propionic/methylacetic acid	22.48 ^d	25.73 ^b	24.65 ^c	28.62 ^a	0.39
Isobutanoic acid	2.13 ^d	2.46 ^b	2.32 ^c	2.55 ^a	0.03
Butanoic acid	15.01 ^c	17.05 ^a	16.25 ^b	17.57 ^a	0.26
Isovaleric/Isopentanoic acid	3.27 ^c	4.36 ^{ab}	4.03 ^b	4.84 ^a	0.19
Valeric/pentanoic acid	2.75 ^b	3.19 ^{ab}	2.99 ^{ab}	3.53 ^a	0.21
Acetate propionate ratio	1.73 ^a	1.34 ^c	1.49 ^b	1.08 ^d	0.03

In comparison to the control group (T1), supplementation significantly decreased ($P < 0.05$) the ruminal pH, ammonia nitrogen ($\text{NH}_3\text{-N}$), methane concentration, acetic acid, and the acetate-to-propionate ratio in T2, T3, and

T4. On the other hand, the supplemented groups had significantly higher levels of total volatile fatty acids (VFAs), as well as iso-butyric, iso-valeric, and valeric acids ($P < 0.05$). The quantities of propionic and butyric acid also rose substantially in T2 and T3, but remained at their lowest in T1.

Important markers of microbial activity and fermentation efficiency include these fermentation characteristics: ruminal pH, $\text{NH}_3\text{-N}$, methane production, and VFA profiles (Anaso et al., 2025b).

The elevated total VFAs, particularly propionic and butyric acids, suggest improved carbohydrate fermentation and a greater supply of metabolizable energy to the host. Butyric acid plays an essential role in stimulating epithelial growth and maintaining intestinal integrity (Butzner et al., 1994; Anaso et al., 2025b), while propionic acid serves as a major gluconeogenic precursor, supporting energy metabolism. Higher iso-butyric acid levels point to increased proteolytic activity and branched-chain VFA production, which may reflect improved microbial protein synthesis (Cardona et al., 2005; Anaso et al., 2025c). The reduction in $\text{NH}_3\text{-N}$ further indicates a more efficient utilization of dietary nitrogen, with decreased proteolysis and reduced nitrogen losses.

The observed ruminal pH range (6.23–6.29) remained within the optimal threshold for fibrolytic microbial activity, demonstrating that essential oil supplementation did not compromise buffering capacity. This outcome corroborates the findings of Ryle & Ørskov (1990), Van Soest (1994), and Anaso et al. (2025b), who emphasized the importance of maintaining stable pH for optimal ruminal fermentation.

Methane reduction in all supplemented groups is in line with other research that found essential oils either reroute metabolic hydrogen into other routes or modify methanogenic archaea (Cobellis et al., 2015; Mahmoud et al., 2025). Bioactive terpenes and phenolics that block methanogens or divert fermentation from the synthesis of acetate are mostly responsible for this impact (Ohene Adjei et al., 2008; Wang et al., 2009; Hernandez et al., 2017). Nonetheless, variability in methane outcomes across essential oil types and dosages has been reported, with some studies observing no significant effects (Benchaar et al., 2007b; Tomkins et al., 2015; Beauchemin & McGinn, 2006).

Overall, supplementation with PTN, DOV, and especially their mixture significantly modulated ruminal fermentation toward reduced nitrogen losses, enhanced energy efficiency, and mitigated methane emissions. These results demonstrate how PTN and DOV essential oils can be used as sustainable phytogenic feed additives to increase ruminant production and promote ecological consciousness.

CONCLUSION

Supplementation with essential oils derived from *Piliostigma thonningii* (PTN), *Daniellia oliveri* (DOV), and their 1:1 mixture (MEO) improved milk yield and composition, enhanced immune competence and antioxidant defense mechanisms, and optimized rumen fermentation characteristics in lactating West African Dwarf does. The treatments also reduced oxidative stress indicators and predicted methane emissions. The combined essential oil treatment (MEO) consistently produced the most pronounced responses, suggesting synergistic interactions between PTN and DOV bioactive compounds. These findings indicate that essential oils extracted from PTN and DOV, particularly when used in combination, represent effective phytogetic feed additives for improving productivity, physiological resilience, and environmental sustainability in climate-smart dairy goat production systems.

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