Research Article

Meta-Analysis of *Andrographis paniculata* Effects on Ruminant Performance and Meat Quality

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Abstract | This research aims to evaluate the effects of *Andrographis paniculata* on livestock diets, specifically focusing on rumen fermentation characteristics, ruminant performance, and meat quality. A meta-analysis was conducted using data from 14 experiments across 10 articles. Supplementation with *A. paniculata* (0–15 g/kg DM) did not significantly affect in vitro organic matter digestibility (IVOMD), pH, acetate (C_2), or ruminal methane concentration. However, it significantly reduced total short-chain fatty acids (SCFA), particularly propionate (C_3) and butyrate (C_4) ($p < 0.01$). Ammonia (NH_3) concentration showed a non-significant decrease in NH_3 concentration. While feed intake remained unaffected, *A. paniculata* improved average daily gain (ADG; $p < 0.04$), feed efficiency ($p < 0.01$), and reduced feed conversion ratio (FCR). It also numerically increased hot carcass weight (HCW; $p = 0.058$) and meat redness (a*; $p = 0.063$), while reducing shear force ($p = 0.066$). Overall, *A. paniculata* supplementation enhances ruminant performance and meat quality without compromising digestion.

Keywords | Andrographis, Methane, Performance, Ruminants, Supplement, Feed

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INTRODUCTION

The livestock industry has increasingly adopted *Andrographis paniculata*, which is an herbal plant, particularly within organic livestock campaigns. This herbal plant, widely known for its medicinal properties, is rich in bioactive compounds such as saponins, alkaloids, phenolic compounds, tannins, and flavonoids. These compounds contribute to enhanced feed intake, nutrient digestibility, immune system regulation, endocrine stimulation, reduction in rumen protozoa populations, and mitigation of methane emissions (Budan *et al*., 2013; Odhaib *et al*., 2021; Avila-Nava *et al*., 2023; Antonius *et al*., 2024). Adding specific secondary chemical compound extracts to animal diets offers the possibility to change ruminal fermentation, improve fiber digestion, decrease greenhouse gas emissions, and decrease nitrogen excretion (Sarma *et al*., 2023).

Andrographis paniculata is an herbal plant commonly located in South India, North India, Sri Lanka, Thailand, Malaysia, Brunei, Java, and Borneo Island (Subramanian *et al*., 2012). While most of these plants are native to Asia, their utilization as a source of bioactive compounds has spread globally, with significant usage noted in Europe (Biró-Sándor 2014; Damasceno *et al*., 2022). Immune function, and intestinal health in poultry (Fayed *et al*., 2023; Jahja *et al*., 2023; Liu *et al*., 2023), while in pigs, it enhances reproductive performance and mitigates heat stress (Papatsiros *et al*., 2022; Tummaruk *et al*., 2024). Several investigations on the addition of *A. paniculata* in goat diet have been conducted. The use of *A. paniculata* in goat diets attempts to enhance growth performance, maintain health, and increase meat quality (Karami *et al*., 2011; Yusuf *et al*., 2014, 2018a; Roslan *et al*., 2016). Furthermore, its impact on ruminal methane production and fermentation profiles has been reported to vary depending on dosage and substrate (Yusuf *et al*., 2012; Sasongko *et al*., 2023). The effects of *A. paniculata* on methane production and protein metabolism are likely indirect, mediated through modulation of rumen microbiota. Findings regarding growth performance improvements are primarily derived from in vivo studies, although some *in vitro* experiments also support these claims (Yusuf *et al*., 2017; Priyoatmojo *et al*., 2021).

Despite these findings, there remains a significant research gap in synthesizing the effects of *A. paniculata* specifically as a feed additive in ruminant diets. Previous meta-analyses and reviews have predominantly focused on the bioactive components of herbal plants rather than the specific contributions of individual species (Sari *et al*., 2022; Brutti *et al*., 2023; Pepeta *et al*., 2024). To our knowledge, no comprehensive evaluation has been conducted to date examine the aggregated effects of *A. paniculata* on ruminant performance, rumen fermentation characteristics, and meat quality.

This study aims to address this gap by conducting a meta-analysis to evaluate the efficacy of *A. paniculata* as a dietary supplement for ruminants. The findings will contribute to a deeper understanding of its potential role in improving ruminant production systems and advancing sustainable livestock management practices.

MATERIALS AND METHODS

Literature search

A literature search was performed using Harzing's Publish or Perish version 8 (Windows GUI Edition) with the keywords Andrographis, paniculata, and feed. From 2010 to 2024, 200 publications were identified on Scopus®, PubMed®, and Google Scholar®. Due to the limited literature, the study focused on scientific articles in journals and conference articles.

Article selection

The article selection process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page *et al*., 2021). The PRISMA guidelines were created to assist systematic reviewers in clearly explaining the reasons for conducting the review, the methods they used, and their findings. In the past ten years, there have been significant developments in the methodology and terminology of systematic reviews. The criteria for selection were: (1) The article must be published in a journal or scientific proceedings. (2) The article must be based on experimental research. (3) The study must involve the use of *A. paniculata* as a feed for ruminants. (4) The focus of the study must be on *A. paniculata* either as a standalone or mixed supplement. (5) Details regarding the concentration of *A. paniculata* (g/kg DM) are available. (6) The study must report at least one parameter related to rumen fermentation, animal performance, feed intake, or carcass and meat quality. (7) The research must be conducted on common ruminant species, such as cattle, sheep, or goats, under controlled experimental conditions. Figure 1 shows the graph depicting the literature selection process. Following a comprehensive review of all articles, a total of 10 publications, encompassing 14 experiments, were included in the database, and are detailed in Table 1.

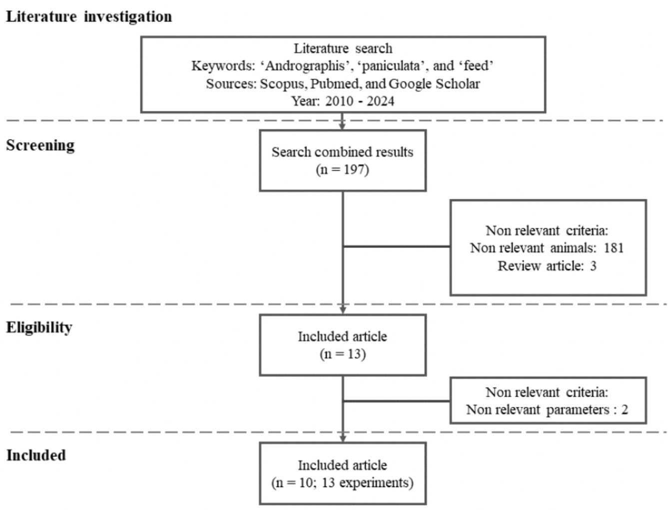

Figure 1: Article selection flowchart according to the PRISMA protocol (Page *et al*., 2021).

Table 1 contains detailed information on the basal rations, supplementation levels, observation types, and animals used. These details will be thoroughly discussed in the results and discussion sections. The compiled parameters include rumen fermentation, average daily gain, feed intake, and feed efficiency, as well as carcass and meat quality. Rumen fermentation parameters include in vitro organic matter digestibility (IVOMD), pH, ammonia (NH_3),

Table 1: Studies included in the meta-analysis of influence of *Andrographis paniculata* addition in feed rations on ruminants' performance.

No.	Reference	Basal rations	Supplementation level (g/kg DM)	*In vitro/ in vivo*	Animal
1	Sasongko *et al.* (2023)	Sorghum forage, *Pennisetum purpureu*m cv. Mott, Pennisetum purpupoides, *Indigofera zollingeriana*, Cocoa pod husk	0 and 10	*In vitro*	-
2	Priyoatmojo *et al.* (2021)	Rice straw and concentrate	0 and 10	*In vitro*	-
3	Galván *et al.* (2021)	milk replacer and commercial concentrate	0, 3, 4, and 5	*In vivo*	Dairy calves
4	Yusuf *et al.* (2018b)	oil palm frond, rice husk, naiper grass and concentrate	0 and 15	*In vivo*	Goat
5	Roslan *et al.* (2016)	urea-treated rice straw and concentrate	0 and 10	*In vivo*	Goat
6	Yusuf *et al.* (2014)	oil palm frond, rice husk, fresh grass and concentrate	0 and 15	*In vivo*	Goat
7	Yusuf *et al.* (2012)	no information	0 and 10	*In vitro*	-
8	Karami *et al.* (2011a)	palm kernel cake, oil palm frond, and concentrate	0 and 5	*In vivo*	Goat
9	Karami *et al.* (2011b)	palm kernel cake, oil palm frond, and concentrate	0 and 5	*In vivo*	Goat
10	Karami *et al.* (2010)	palm kernel cake, oil palm frond, and concentrate	0 and 5	*In vivo*	Goat

DM: dry matter.

short-chain fatty acids (SCFA), acetate (C_2), propionate (C_3), butyrate (C_4), and methane (CH_4). Carcass quality parameters consist of hot carcass weight (HCW) and drip loss. Meat quality parameters include cooking loss, shear force, lightness (*L**), redness (*a**), and yellowness (*b**).

Statistical analysis

A statistical meta-analysis of the dataset, which had consistent units of measurement, was conducted using linear mixed model (LMM) methodology (St-Pierre, 2001; Sauvant *et al.*, 2008). Multiple studies were treated as random effects, whereas the *A. paniculata* addition was treated as a fixed effect, assuming that the true effect size remains consistent across all included studies. The following statistical models were used:

$$Yij=B0+BXij+B2Xij2+si+biXij+eij$$

Where; Yj= dependent variable, B = overall intercept across all studies (fixed effect), B1= linear regression coefficient Y on X (fixed effect)., 2= Y squared regression coefficient on X (fixed effect), Xij= predictor value of continuous variable (nutrition level), si= random effect of study I, bi= random effect of study i on the regression coefficient Y on X in study I, eij= unexplained residual error.

Linear Mixed Models (LMM) are more appropriate for identifying quantitative relationships in the data. The traditional approach, which uses simple regression methods to integrate information across studies, is statistically flawed and is likely to lead to incorrect conclusions. The observations in the study are unbalanced, which may affect the results and neglecting the study effects during regression analysis results in biased estimates of regression coefficients and inflated standard errors. Since study effects are essentially random, LMM provides a better method for analyzing such data. The statistical analysis was carried out using R software version 4.1.2 (R Core Team, 2022) and the lme4 package version 1.1-35.3 (https://cran.r-project.org/web/packages/lme4/index.html). Significance was determined through one-way analysis of variance, with p-values considered significant if less than 0.05 ($p<0.05$) and tending towards significance if between 0.05 and 0.1.

RESULTS

Summary of the selected research papers

In this meta-analysis investigation, we carefully chose studies published from 2010 onwards. We have collected a group of ten papers, including seven studies conducted *in vivo* and three studies conducted *in vitro*. Among the *in vivo* experiments, six papers employed goat commodities, whereas one research employed dairy cattle commodities. *A. paniculata* administration levels range from 0-15 g/kg DM. Most of the basic feed sources utilized originate from agricultural and plantation byproducts, such as rice straw, oil palm frond, palm kernel cake, and cocoa pod husk. Additionally, there are available sources of forage such as Sorghum forage, *Pennisetum purpureum* cv. Mott, *Pennisetum purpupoides*, and *Indigofera zollingeriana*.

Influence of *A. paniculata* addition on ruminal fermentation characteristics

The fermentation characteristics in the rumen following the addition of *A. paniculata* can be observed in Table 2. The incorporation of *A. paniculata* did not have a significant impact on IVOMD parameters, pH values, C_2 concentration, and methane concentration. *A. paniculata*

Table 2: Influence of *Andrographis paniculata* addition on rumen fermentation characteristics.

Parameter	Unit	n	Intercept	SE Intercept	Slope	SE slope	p-value	RMSE
IVOMD	%	18	54.88	2.959	-0.052	0.046	0.281	0.70
pH		21	6.901	0.080	-0.001	0.002	0.596	0.04
NH_3	mg/100 ml	21	34.64	7.020	-0.134	0.070	0.080	1.13
SCFA	mM	11	29.37	6.370	-1.486	6.370	0.043	0.87
C_2	mM	17	57.57	7.042	-0.206	0.177	0.276	2.51
C_3	mM	17	16.02	1.910	-2.118	1.912	0.001	0.51
C_4	mM	17	8.740	1.530	-1.662	1.527	0.001	0.32
Methane	mmol/100 mg IVOMD	14	19.12	0.612	0.078	0.045	0.128	0.61

IVOMD: *in vitro* organic matter digestibility (%); NH_3: ammonia (mg/100 ml); SCFA: single chain fatty acids (mMol); C_2: acetate (mMol); C_3: propionate (mMol); C_4: butyrate (mMol); SE: standard error; RMSE: root mean square error. SCFA provide energy for ruminants, while NH_3 supports microbial protein synthesis. Their balance optimizes rumen function, enhancing feed efficiency and animal growth.

Table 3: Influence of *Andrographis paniculata* addition on average daily gain, feed intake and feed efficiency.

Parameter	Unit	n	Intercept	SE intercept	Slope	SE slope	p-value	RMSE
ADG	g/d	9	59.93	35.35	2.924	1.070	0.040	10.71
Feed intake	g/d	7	829.1	58.96	10.51	6.977	0.192	92.86
Feed efficiency		9	7.778	2.555	-0.298	0.047	0.001	0.460

ADG: average daily gain (g/d); SE: standard error; RMSE: root mean square error.

has been demonstrated to significantly reduce total SCFA ($p<0.05$), as well as C_3 and C_4 particularly ($p<0.01$). The addition of *A. paniculata* resulted in a modest reduction ($p=0.08$) in the concentration of NH_3. Although the decrease in NH_3 concentration was not statistically significant ($p= 0.08$), it may have biological relevance due to its association with improved nitrogen metabolism efficiency in the rumen. TVFA (mM) = $29.37 + -1.486X + 0.165X^2$; n = 11; p-value = 0.043; RMSE = 0.869. propionate (C_3) (mMol) = $16.02 + -2.119X + 0.203X^2$; n = 17; p-value = 0.001; RMSE = 0.514. butyrate (C_4) (mMol) = $8.744 + -1.662X + 0.158X^2$; n = 17; p-value = 0.001; RMSE = 0.325.

The absence of a significant effect of *A. paniculata* on IVOMD parameters, pH levels, C_2 concentration, and methane production could be attributed to its minimal influence on microbial activity and substrate breakdown in the rumen. Since IVOMD and pH are largely determined by overall microbial fermentation efficiency, *A. paniculata* supplementation may not have induced substantial changes. Likewise, C_2 (acetate), which is mainly derived from fiber digestion, appears to remain unaffected.

On the other hand, *A. paniculata* significantly lowered total SCFA levels ($p < 0.05$), with a notable reduction in C_3 (propionate) and C4 (butyrate) ($p < 0.01$). This effect may be linked to its impact on microbial populations involved in short-chain fatty acid synthesis. The bioactive compounds present in *A. paniculata* might selectively suppress specific microbial pathways, leading to decreased SCFA production, particularly in propionate and butyrate. Furthermore, the quadratic equations indicate a non-linear dose-response relationship, suggesting that moderate doses of *A. paniculata* may have distinct effects compared to higher concentrations. The reduction in total SCFA followed a quadratic pattern, with optimal effects observed at moderate doses (0–10 g/kg DM).

Influence of *A. paniculata* addition on average daily gain, feed intake and feed efficiency

The impact of adding *A. paniculata* on livestock production, including ADG, feed intake, and feed efficiency, is shown in Table 3. The addition of *A. paniculata* has no impact on feed intake parameters, despite it can enhance ADG ($p<0.04$) and feed efficiency ($p < 0.01$) by reducing FCR.

Influence of *A. paniculata* addition on carcass and meat quality

Table 4 presents the effects of incorporating *A. paniculata* on the characteristics of ruminant carcasses and meat. Adding *A. paniculata* into the diet showed a numerical increase the HCW value ($p = 0.058$) and the redness (a*) of meat ($p=0.063$). The addition of *A. paniculata* tend to a decrease in the shear force value ($p = 0.066$) and TBARS ($p = 0.058$). Although the characteristics of drip loss, cooking loss, lightness (L*), and yellowness (b*) did not show any significant differences.

Table 4: Influence of *Andrographis paniculata* addition on carcass and meat quality.

Parameter	Unit	n	Intercept	SE Intercept	Slope	SE Slope	p-value	RMSE
HCW	kg	5	10.76	1.219	0.317	0.096	0.058	0.90
Drip.loss	%	5	3.971	1.166	0.003	0.013	0.844	0.10
Cooking.loss	%	5	28.28	2.106	-0.129	0.083	0.254	0.69
Shear force	kg	5	2.792	1.634	-0.026	0.007	0.066	0.06
L*		7	33.02	1.379	-0.078	0.038	0.130	0.33
a*		7	9.642	0.837	0.139	0.050	0.063	0.47
b*		7	9.194	1.412	-0.029	0.014	0.126	0.12
TBARS	mg MDA/kg	7	3.080	2.160	-0.229	2.159	0.058	0.10

HCW: hot carcass weight (kg); *L**: lightness; *a**: redness; *b**: yellowness; TBARS: thiobarbituric acid reactive substances (mg MDA/kg); MDA: Malondialdehyde; SE: standard error; RMSE: root mean square error. HCW is crucial as it reflects the overall meat yield and economic value. TBARS indicate lipid oxidation, affecting meat quality, shelf life, and flavor. Controlling these factors ensures better meat quality and marketability.

DISCUSSIONS

In the compiled studies, *A. paniculata* was widely used in goat rations, accounting for 60% of the total studies. This widespread implementation could be due to goats' high tolerance for the herb's bitter taste. Goats' high tolerance for bitter flavors has been reported in previous studies (Dias-Silva and Filho, 2021). *Andrographis paniculata*, in English, is referred to as the "King of Bitters" or Green Chiretta. Goats exhibit a higher tolerance for bitter forage compared to sheep and frequently favour browsing plants over grasses (Dias-Silva and Filho, 2021). Due to their curious disposition and tolerance for "bitter" or high-tannin substances, goats may consume unpleasant weeds and wild bushes that could be toxic (Luginbuhl *et al*., 1995).

We recognized that the number of compiled studies is relatively small compared to typical meta-analyses. This could be because the use of *A. paniculata* is predominantly confined to Southeast Asian countries. The application of this herb is deeply rooted in the traditions and cultural practices of local farmers. Nonetheless, this provides a fascinating topic for discussion.

Overall, the results of our meta-analysis indicated that several rumen fermentation characteristics, including SCFA, C_3, C_4, and NH_3, decreased in rations supplemented with *A. paniculata*. This effect was directly attributed to the secondary metabolite present in *A. paniculata*. Dwivedi *et al*. (2021) identified the primary metabolite compounds in *A. paniculata*, including Neoandrographolide, and rographolactone, 14-dehydroxy-11,12-didehydroandrographolide, skullcap flavone I, and 5-Hydroxy-2′,7,8-trimethoxyflavone. Besides the andrographolide compounds, the leaves also contain abundant tannins. The total tannins in *A. paniculata* leaves were measured to be approximately 20.40 ± 1.06 mg/g tannic acid equivalent, and the condensed tannins were around 8.44±0.17 mg/g leucocyanidin equivalent (Priyoatmojo *et al*., 2021). Eighteen species of anaerobic fungi from six genera present in the rumen serve to expose cellulose components to bacteria, facilitating SCFA synthesis (Ku-Vera *et al*., 2020). The diverse secondary metabolites in *A. paniculata* could influence the microbial populations within the rumen. We hypothesize that the tannins in *A. paniculata* are significantly influential. Phenolic compounds, particularly tannins, act as inhibitors and deactivators of cellulolytic enzymes and, to a larger extent, β-glucosidase (Ximenes *et al*., 2011). Contradictory results were observed by Priyoatmojo *et al*. (2021) and Yusuf *et al*. (2017), where *A. paniculata* did not significantly impact total SCFA content. The appropriate dosage of herbs is crucial for maintaining the stability of rumen fermentation conditions (Szulc *et al*., 2020; El-Tawab *et al*., 2021).

The reduction in SCFA concentration following the addition of *A. paniculata* was observed from the decrease in C_3 and C_4 concentrations (Table 2). Sasongko *et al*. (2023) showed a reduction in C_3 concentration following the addition of *A. paniculata* herbs, alongside a basal feed of *Pennisetum purpupoides*, *Indigofera zollingeriana*, and cocoa pod husk. Variations in C_3 concentration may result from the impact of phenolic compounds in *A. paniculata* on the population of propionic bacteria within the rumen. Propionic bacteria play a significant role in gluconeogenesis (Azzaz *et al*., 2019). The total SCFA concentration showed a positive correlation with the genera *Solibacillus*, *Ruminococcus_1*, and *Ruminococcaceae_UCG-010*, while it was negatively correlated with *Trichococcus*. More specifically, butyrate exhibited a negative correlation with the genus *Roseburia* (Xie *et al*., 2023). The addition of herbal materials containing diterpenoids will reduce *Firmicutes*, which play a role in degrading cellulose and converting it into SCFA. This bacterium has also been implicated in host immune responses, inhibiting the invasion of opportunistic pathogens and preventing inflammation (Gruninger *et al*., 2014; Zhang *et al*., 2015). According to El-Tawab *et* *al.* (2021), a blend of various herbal plants has decreased the concentration of SCFA in rumen fluid. This effect is attributed to the impact of essential oils on protozoa, fungi, and rumen bacteria populations. Based on our meta-analysis, the optimal dosage for *A. paniculata* incorporation is 0-15 g/Kg DM. Moreover, a higher dosage shows a diminishing return. Wanapat *et al.* (2013) reported that this phenomenon is dose-dependent.

The incorporation of *A. paniculata* into ruminant diets was found to reduce ammonia (NH_3) concentrations in the rumen (p=0.08). Based on previous findings (Yusuf *et al.*, 2012; Roslan *et al.*, 2016; Priyoatmojo *et al.*, 2021), the reduction in NH_3 concentration might have been directly linked to a decline in the rumen microbial population following adding *A. paniculata*. The antimicrobial properties of plant bioactive components arise from their interaction with the cell membranes of rumen microbes, disrupting the stability of the bacterial cell membrane's bilayer. This interaction consequently reduces the enzymatic activity produced by rumen microorganisms (Bature *et al.*, 2024). The secondary metabolites in the herb appeared to have directly impacted the functionality of microbial enzymes rather than reducing protein degradation. Over the years, it became evident NH_3 concentration alone did not fully explain the effects of degradable protein on microbial growth (Dewhurst and Newbold, 2022). The application of different herbs similarly demonstrated comparable effects. Sinz *et al.* (2019) documented that adding extracts from acacia, gambier, grape seed, and cranberry significantly decreased ammonia levels in the incubation fluid. The decline in NH_3 concentration, similar to the process of SCFA reduction, could be attributed to the antibacterial properties of the Andrographolide compound. However, this hypothesis remains weakly clarified. Furthermore, the tannin concentration in *A. paniculata* may have a definitive influence. The tannin extracts mainly contributed to the mitigation effects by reducing ammonia levels by approximately 31% (Foggi *et al.*, 2022). Moreover, several phenolic compounds also significantly reduced NH_3 levels (Huang *et al.*, 2023). The reduction in SCFA and NH_3 levels warrants attention when administering this herbal additive, as these parameters are crucial indicators of the efficiency of the digestive and absorption processes in ruminant digestion (Lu *et al.*, 2019).

In our meta-analysis, the incorporation of *A. paniculata* did not influence methane gas production. This could refer to two aspects: (1) The active compounds in *A. paniculata* did not have a substantial influence on methanogenic Archaea, and (2) the C_3 component also declined following the administration of *A. paniculata*. The C_3 production method utilizes H^+ ions, hence competing with CH_4 production (Wang *et al.*, 2018). Sari *et al.* (2022) identified two reasons for the inconsistency of bioactive chemicals in mitigating CH_4 emissions. At first, various sources possess differing quantities of bioactive compounds. Secondly, the formulation of the basal diet can influence the efficacy of bioactive chemicals derived from various sources by altering rumen metabolism. The mechanisms of action of most plant extracts are mostly ambiguous, with almost all research relying on *in vitro* fermentation experiments (Sun *et al.*, 2021). The impact of *A. paniculata* on methane emissions was evaluated through a compilation of both *in vitro* and *in vivo* studies. The outcomes of these studies often did not align with initial expectations. Variations in results between *in vitro* and *in vivo* studies are commonly influenced by various environmental factors. In this context, feed composition significantly contributes to the observed differences. Administering herbs to ruminants primarily fed with forage led to a more pronounced reduction in methane emissions (Della Rosa *et al.*, 2022). Conversely, in rations with a higher concentrate proportion, the reduction in methane emissions was less consistent. This inconsistency arises because methane measurements are sensitive to drops in rumen pH, which occur when high percentages of concentrate are given (Vázquez-Carrillo *et al.*, 2020). The absence of a significant effect of *Andrographis paniculata* on methane production may be attributed to the composition and concentration of its bioactive compounds. While *A. paniculata* contains diterpenoids, flavonoids, and polyphenols, its lack of substantial tannin or saponin content could limit its anti-methanogenic potential, as these compounds have been shown to inhibit methanogenic archaea (Patra and Saxena, 2010). Additionally, variations in extraction methods and plant part utilization may influence bioactive compound availability, impacting its efficacy in modulating rumen fermentation (Salem *et al.*, 2012).

Incorporating *A. paniculata* did not negatively impact pH and IVOMD levels, although SCFA and NH_3 tended to decline. This finding demonstrates that adding *A. paniculata* herb does not adversely affect the ruminant digestive system. Numerous prior investigations have presented a wide variety of results. Adding herbal supplements to ruminant diets can lower IVOMD parameters by inhibiting the growth of *fibrolytic* and *proteolytic* bacteria (Rira *et al.* 2015; Kisworo *et al.*, 2017). Conversely, numerous previous studies have indicated an enhancement in microbial activity following the administration of herbs, leading to an increase in IVOMD (Jain *et al.*, 2017; Szulc *et al.*, 2020; Kapp-Bitter *et al.*, 2021). Moreover, Kapp-Bitter *et al.* (2021) showed an increase in IVOMD despite a decrease in NH_3. The variations in findings could be caused by interactions between supplements and nutritional components in the basal diet and from variations in the experimental environment (Jain *et al.*, 2017; Rahmy *et al.*, 2019; Priyoatmojo *et al.*, 2021).

Our meta-analysis results indicated that adding *A. paniculata* positively influenced ruminant growth, as shown by ADG. Yusuf *et al.* (2017) demonstrated that dietary supplementation of *A. paniculata* increased the populations of *Ruminococcus flavefaciens*, *Ruminococcus albus*, and *Fibrobacter succinogenes* in the rumen, hence enhancing nutrient digestibility in goats. During the weaning phase, herbal treatment may influence gene expression by enhancing lipid, carbohydrate, and protein metabolism, as well as immunological response (Díaz-Galván *et al*., 2021). Adding bioactive compounds into the diets of dairy cows positively influenced dairy products, resulting in enhanced antioxidant capacity and reduced levels of metabolites such as malondialdehyde (Avila-Nava *et al*., 2023). Kapp-Bitter *et al.* (2021) showed that administering *A. paniculata* can decrease rumen NH_3 levels, therefore minimizing the risk of ammonia toxicity.

Administering herbs indirectly enhances the health of ruminants, thereby boosting productivity. *Andrographis paniculata* extract exhibits potential as an anticoccidial due to its composition of andrographolide, flavonoids, alkaloids, saponins, phenols, tannins, and other steroids (Irianti *et al*., 2022). In addition to enhancing ADG, adding *A. paniculata* may improve feed efficiency. Enhancing feed efficiency will boost the feed utilization ratio, decrease feed consumption, and mitigate the environmental implications of livestock farming (Omontese *et al*., 2022). Alterations in the microbial environment following herbal treatment are the primary factors contributing to enhanced feed efficiency. The rumen ecosystem of bacteria can affect feed efficiency indicators, including ADG, feed consumption, and body weight gain (Xu *et al*., 2022). Ruminant performance after the administration of *A. paniculata* varies in accordance with the type of basal diet, akin to rumen fermentation parameters. The impact of herbal supplementation on livestock performance is influenced by the proportion of forage to concentrate in the diet (Vázquez-Carrillo *et al*., 2020; Della Rosa *et al*., 2022). The degree of response to herbal supplements in ruminants is also influenced by the species of livestock and their physiological status (Mendoza-Martínez *et al*., 2024).

Regarding various carcass and meat quality parameters, the inclusion of *A. paniculata* significantly enhanced livestock performance. The addition of *A. paniculata* was observed to increase carcass weight. Interestingly, the increase in the parameters occurred despite *A. paniculata* having no impact on the digestibility of organic matter in the rations. Mahyuddin and Winugroho (2010) reported that the impact of herbs on the carcass and meat yield in ruminants is complex and not easily comprehended. Thus, we hypothesized that the increase in carcass weight could be attributed to several factors: (1) enhanced efficiency of feed conversion into body mass; (2) the antioxidant properties of *A. paniculata* reducing stress levels in livestock; (3) secondary metabolites in *A. paniculata* boosting the immune system, thereby increasing carcass production; and (4) the antimicrobial action of *A. paniculata* maintaining digestive tract health and improving nutrient absorption. The antioxidant activity was evidenced by the reduction in TBARS levels in the meat (Table 4). Bioactive compounds enhance digestive processes and stabilize the gastrointestinal environment, leading to better feed utilization and improved quality of animal products (Bąkowski and Kiczorowska, 2021). These results elucidate the mechanism by which the addition of *A. paniculata* enhances meat tenderness, as evidenced by reduced shear force. Previous studies have demonstrated that nutritional interventions involving herbs and phytochemicals operate at both cellular and molecular levels. They activate cell signalling pathways that influence crucial metabolic processes and essential physiological functions. These interventions modulate metabolic, immune, and antioxidant responses to mitigate inflammation, immune dysregulation, and impaired metabolic adaptation during stress conditions (Kotsampasi *et al*., 2024).

Shear force is a widely used measure to assess tenderness, a critical aspect of the eating quality of ruminant meat (Al-Moadhen *et al*., 2024). *Andrographis paniculata* was observed to enhance meat tenderness in rations. Phenolic compounds in herbs have been shown to enhance meat tenderness significantly (Morán *et al*., 2012; Yusuf *et al*., 2018b). Previously, it was suggested that the bioactive components in *A. paniculata* might help reduce oxidative stress in livestock, thereby improving meat quality. These bioactive compounds in herbs acted as antioxidants and lowered TBARS levels (Avila-Nava *et al*., 2023). Numerous active constituents of herbs and spices can inhibit lipid peroxidation by neutralizing free radicals or activating antioxidant enzymes such as catalase, superoxide dismutase, glutathione reductase, and glutathione peroxidase (Karami *et al*., 2011b). A reduction in TBARS values leads to a redder and fresher appearance of the meat. This low TBARS value indicates that myoglobin oxidation in the meat is being prevented following the addition of herbs to the feed. The degradation in meat color quality is typically due to the myoglobin oxidation process (Poveda-Arteaga *et al*., 2023). Salzano *et al.* (2021) also observed that herbal supplements (including red orange and lemon extract) can enhance juiciness and reduce color deterioration. According to Karami *et al.* (2011a), supplementation with *A. paniculata* was demonstrated to enhance meat tenderness and preserve its color by inhibiting lipid oxidation. Additionally, the potential role of *A. paniculata* in modulating muscle proteolysis through its influence on calpain and cathepsin enzyme activity could contribute to improved tenderness (Huff-Lonergan and Lonergan, 2005). The antioxidant activity of *A. paniculata* may also influence myoglobin stability, preventing its oxidation to metmyoglobin, which is responsible for meat discoloration (Faustman *et al*., 2010). Research by Yusuf *et al*. (2014) showed that giving feed containing leaves or all parts of the *A. paniculata* plant to Boer goats increased feed intake, increased body weight, feed efficiency, and live weight. The ratio of meat to fat, meat to bone, and meat composition have also improved. Improvements in these parameters can result in better quality meat, such as lower fat content and a more favorable texture, which in turn can increase consumer preference and the marketability of the meat product.

The research compiled on the incorporation of *A. paniculata* into goat feed reveals several significant findings regarding its advantages and effects on livestock health and productivity. A primary benefit of *A. paniculata* is its acceptance in goat diets, as these animals exhibit a high tolerance for the plant's bitter flavor, enabling them to consume potentially toxic weeds or shrubs that other species might avoid. Conversely, it is noted that certain parameters, including short-chain fatty acids (SCFA), C_3, C_4, and ammonia (NH_3) concentrations in the rumen, decrease following *A. paniculata* supplementation. This phenomenon is attributed to the secondary metabolites present in the plant, such as tannins and andrographolide, which function as enzyme inhibitors and influence microbial activity in the root (Anwar *et al*., 2023). However, the implications of these changes on methane production and other related factors warrant further investigation. Moreover, the findings indicate enhancements in ruminant performance associated with *A. paniculata* supplementation, including improvements in Average Daily Gain (ADG), feed efficiency, and carcass weight. An additional advantage is the positive impact on meat quality, as *A. paniculata* appears to mitigate oxidative stress, enhance tenderness, and maintain meat color and freshness by limiting myoglobin oxidation. This suggests that *A. paniculata* may not only bolster livestock health and productivity but also elevate the quality of animal-derived products. Nonetheless, the variability in results highlights that the effects of *A. paniculata* are influenced by factors such as dosage, the type of base feed, and experimental conditions. Consequently, further research is essential to elucidate the mechanisms and long-term consequences of this supplementation. In summary, despite the limitations stemming from the limited number of studies reviewed, the findings offer valuable insights into the potential of *A. paniculata* as a feed additive capable of enhancing both productivity and the quality of livestock products. Additional research is necessary to investigate the interactions among the secondary metabolites found in *A. paniculata.*

CONCLUSION

Andrographis paniculata in livestock feed selectively influenced ruminal fermentation by reducing total short-chain fatty acids (SCFA), particularly propionate (C_3) and butyrate (C_4), while having no significant effect on IVOMD, pH, acetate (C_2), or methane production. This suggests potential alterations in energy metabolism pathways that could indirectly influence methane production. Supplementation with *A. paniculata* improves ruminant growth and meat quality. However, its impact on rumen fermentation is complex, with reductions in total SCFA but no significant effects on methane production or digestibility. While *A. paniculata* does not appear to be effective for methane mitigation, its influence on fermentation profiles warrants further research to assess long-term implications for ruminant nutrition and productivity. To address the limitations identified in this study, further investigations with larger datasets and various ruminant species are necessary.

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NOVELTY STATEMENT

This study provides the first quantitative synthesis of the effects of A. paniculata supplementation on rumen fermentation, animal performance, and meat quality in ruminants. The findings demonstrate that while digestibility and ruminal parameters remain largely unaffected, A. paniculata significantly enhances average daily gain, feed efficiency, and key meat quality attributes, highlighting its potential as a functional phytogenic feed additive in ruminant nutrition.

AUTHOR'S CONTRIBUTION

WTS designed the experiment, data tabulation, wrote the first draft, and revised the manuscript; DAA and AJ supervised the experiment and revised the manuscript; MMS analyzed the data, and wrote the first draft manuscript; SW wrote the first draft, and revised the manuscript; TW supervised the experiment, visualization; wrote the first draft, and revised the manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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