EFFECT OF BIOCHAR TREATMENT ON THE IN VITRO DIGESTIBILITY OF TANNIN-RICH BROWSE SPECIES FED TO LACTATING GALLA GOATS IN THARAKA-NITHI COUNTY, KENYA

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ABSTRACT

Goat production in the arid and semi-arid lands (ASALs) of Kenya depends heavily on indigenous browse species such as Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata, which remain available during prolonged dry seasons but contain high concentrations of condensed tannins that depress rumen microbial activity, nutrient digestibility and, ultimately, milk production in lactating Galla goats. Biochar has been proposed as a feed additive capable of adsorbing anti-nutritional compounds and improving rumen fermentation, yet empirical evidence on its effectiveness in tannin-rich indigenous browse remains limited. This study sought to determine the effect of graded biochar inclusion (0%, 1%, 2% and 3% of dietary dry matter) on the in vitro digestibility and fermentation characteristics of the four browse species. Each species was evaluated separately using a Completely Randomized Design with sixteen experimental units, and digestibility was assessed using the in vitro gas production technique with rumen fluid collected from a fistulated donor goat, incubated at 39°C for 96 hours. Cumulative gas production was recorded at 3, 6, 12, 24, 48, 72 and 96 hours, and dry matter degradability (DMD) and organic matter degradability (OMD) were determined from residue analysis. Biochar level had no significant effect on early-phase gas production (3-6 hours, $P > 0.05$) but produced highly significant treatment effects from 12 hours onward ($P < 0.001$) across all four species. At 96 hours, 2% biochar consistently produced the highest cumulative gas volumes, exceeding the untreated control by 12.1% to 17.9% depending on species, and corresponded with the highest pooled dry matter degradability (68.2% versus 61.4% for the control) and organic matter degradability (65.6% versus 58.7%). The 3% inclusion level did not sustain this advantage, indicating a curvilinear rather than linear dose-response relationship. Acacia tortilis recorded the highest condensed tannin concentration (61.83 mg catechin equivalents (CE)/g DM) and Zizyphus mucronata the lowest (31.57 mg CE/g DM), a gradient that broadly tracked the magnitude of the biochar-associated fermentation response. The findings demonstrate that moderate biochar supplementation, at approximately 2% of dietary dry matter, offers a practical, low-cost strategy for mitigating tannin-related digestibility constraints in browse-based diets for Galla goats in Kenyan drylands, with implications for extension advice, feed formulation and further in vivo validation.

Keywords: Biochar, Condensed Tannins, In Vitro Digestibility, Gas Production Technique, Browse Species, Galla Goats, Rumen Fermentation, Arid and Semi-Arid Lands, Kenya.

INTRODUCTION

Goat production occupies a central position in the livelihood systems of Kenya's arid and semi-arid lands (ASALs), where prolonged dry seasons and unreliable rainfall limit the availability of conventional pasture and concentrate feeds. Under these conditions, indigenous browse species such as Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata constitute critical feed resources because they remain accessible even during periods of extreme moisture stress and generally carry moderate to high crude protein concentrations (Belete et al., 2024). However, the practical feeding value of these species is substantially constrained by high concentrations of condensed tannins, polyphenolic compounds that bind dietary protein and structural carbohydrates, suppress fibrolytic microbial activity and depress overall nutrient digestibility (Rira et al., 2022; Tong et al., 2022). Galla goats, the indigenous dairy and meat breed most closely adapted to Kenya's drylands, possess the genetic potential to produce between 1.5 and 2.5 litres of milk per day under adequate nutrition, yet actual on-farm yields typically remain well below this potential because of the nutritional limitations imposed by tannin-rich browse-based diets (Manyeki et al., 2022; Masila et al., 2022).

Interventions such as concentrate supplementation and improved pasture establishment have been proposed to close this productivity gap, but such approaches depend on external inputs that are frequently costly and logistically difficult to sustain in remote pastoral systems. Comparatively little attention has been directed toward low-cost, locally producible interventions capable of improving the utilization of browse resources that pastoral households already have access to. Biochar, a porous, carbon-rich material produced through the pyrolysis of biomass, has recently attracted interest as a ruminant feed additive because its large surface area and high cation exchange capacity enable it to adsorb anti-nutritional compounds, buffer rumen pH and provide attachment sites for fibrolytic microorganisms (Mokhtarpour, 2025; Waheed et al., 2026).

The dominant feed resources for Galla goats consist of woody browse species that contain significant levels of condensed tannins. Their chemical composition often limits efficient nutrient utilization in ruminants. Tannins bind dietary proteins and carbohydrates during rumen fermentation and eventually reduce their accessibility to rumen microorganisms and lowers digestibility of the consumed feed (Kiplagat et al., 2023). Galla goats breed is widely reared by pastoral communities due to its tolerance to drought, resistance to harsh environmental conditions and ability to survive under low- input production systems (Nguyen et al.,2023). Galla goats also possess relatively higher milk production potential compared with many indigenous breeds and can produce approximately 1.5– 2.5 litres of milk per day under improved feeding conditions.

The browse species selected for the study were chosen because they are among the dominant and most accessible indigenous feed resources in Kenya's ASAL regions where Galla goats are commonly reared. Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata remain available even during prolonged dry seasons when herbaceous pastures become scarce (Molepo,2025). The species are known to contain moderate to high crude protein levels that can support rumen microbial activity and animal production. They however contain substantial concentrations of condensed tannins which reduce palatability, digestibility and nutrient utilization in goats (Mashiachidi et al.,2025). Their widespread use by pastoral communities and their nutritional limitations make them suitable candidates for evaluating the effectiveness of biochar as a tannin mitigation strategy aimed at improving forage utilization and milk production in Galla goats.

A growing body of international evidence associates biochar supplementation with improved nutrient digestibility, enhanced feed conversion efficiency and reduced enteric methane output across several livestock species (Ayeneshet & Tenaw, 2025; Czech Journal of Animal Science meta-analysis, 2023), although responses have not been uniform and appear to depend on feedstock source, pyrolysis conditions, inclusion level and the basal diet under evaluation (Dittmann et al., 2024; Lind et al., 2024). Despite this expanding literature, empirical evidence on whether biochar can mitigate the specific digestibility constraints imposed by condensed tannins in browse species typical of Kenyan ASALs remains scarce. This article addresses that gap by reporting on the first specific objective of a wider Master of Science investigation, namely the determination of the effect of graded biochar treatment on the in vitro digestibility of Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata.

Statement of the Problem

Goat production is a key livelihood activity in the arid and semi-arid lands (ASALs) of Kenya. The browse resources are often rich in nutrients but are constrained by high levels of condensed tannins which reduce digestibility, feed intake and overall animal productivity (Belete et al., 2024). Such a limitation contributes to low milk yields and reduced efficiency of goat production systems (Belete et al., 2024). Biochar has recently emerged as a potential feed additive in ruminant nutrition due to its ability to adsorb anti-nutritional compounds and improve rumen function. Galla goats depend primarily on tannin-rich browse species that interfere with rumen fermentation, reduce nutrient digestibility and limit the efficiency with which animals convert available forage into productive output. Consequently, their milk productivity remains considerably below the genetic potential of the breed. While biochar supplementation has been proposed as a strategy for improving rumen fermentation and feed utilization in ruminants generally, empirical evidence on its effectiveness in improving the in vitro digestibility of the specific tannin-rich browse species relied upon by Galla goats in Kenya's drylands remains limited. This gap constrains the ability of livestock nutritionists and extension officers to recommend evidence-based biochar inclusion levels for browse-based diets in ASAL production systems.

Objective of the Study and Hypothesis

The objective of this article was to determine the effect of biochar treatment on the in vitro digestibility of Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata. The study was guided by the following null hypothesis:

H01: The effect of biochar treatment on the in vitro digestibility of Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata is similar.

Significance of the Study

The findings are of practical value to several categories of stakeholders. Livestock farmers and pastoralists in ASAL counties can draw on the results to inform decisions on treating browse feeds with locally producible biochar to improve forage utilization without relying on costly external concentrates. Animal nutritionists and feed formulators may use the evidence to guide recommended biochar inclusion levels when designing browse-based supplementary diets for goats. Livestock extension officers can apply the findings in advisory work supporting pastoral households seeking practical, low-cost strategies for improving feed utilization during dry seasons. Finally, the study extends the empirical literature on biochar as a tannin-mitigation strategy by providing species-specific, laboratory-validated evidence for browse resources of direct relevance to Kenya's drylands.

Scope of the Study

The study was confined to an in vitro evaluation of four browse species, Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata, at four biochar inclusion levels (0%, 1%, 2% and 3% of feed dry matter), conducted under controlled laboratory conditions at Tharaka University. The evaluation focused on cumulative gas production, dry matter degradability, organic matter degradability and condensed tannin concentration as indicators of fermentation and digestibility response. The study did not extend to in vivo animal performance, methane emission quantification or the nutritional composition of milk, which fall outside the objective addressed in this article.

Theoretical Framework

Tannin-Protein Complexation Theory

The tannin-protein complexation theory holds that condensed tannins bind reversibly or irreversibly with dietary and microbial proteins to form stable complexes that resist enzymatic hydrolysis, thereby reducing the fraction of protein and associated substrate available for microbial fermentation in the rumen (Besharati et al., 2022). At low concentrations, this mechanism can be nutritionally advantageous because it partially protects dietary protein from excessive ruminal degradation, increasing the flow of undegraded protein to the lower digestive tract (Loregian et al., 2023). At the higher concentrations typical of tropical browse species, however, the theory predicts that complexation extends beyond protein to structural carbohydrates, inhibiting fibrolytic enzymes such as cellulases and proteases and depressing overall digestibility (Tong et al., 2022). This theory provides the conceptual basis for interpreting the depressed baseline digestibility observed in the untreated (0% biochar) browse treatments in this study.

Adsorption Theory of Biochar Action

The adsorption theory explains biochar's proposed mode of action through its physicochemical properties, specifically its highly porous structure, extensive internal surface area and high cation exchange capacity, which together enable it to bind polyphenolic compounds, toxic metabolites and excess ammonia within the rumen environment (Mokhtarpour, 2025). By adsorbing part of the tannin fraction, biochar is theorised to reduce the formation of inhibitory tannin-protein and tannin-fibre complexes, thereby restoring greater accessibility of nutrients to rumen microorganisms (Hu et al., 2026). The theory further predicts a dose-dependent response up to a threshold inclusion level, beyond which additional biochar provides diminishing marginal benefit, and may even begin to dilute dietary energy density or interfere with feed physical characteristics (Waheed et al., 2026). This theoretical expectation directly informs the interpretation of the curvilinear response observed between 2% and 3% biochar inclusion in the present study.

Rumen Microbial Ecology Theory

Rumen microbial ecology theory frames digestibility as an emergent property of the interaction between feed substrate characteristics and the composition, attachment and metabolic activity of the resident microbial population (Chang et al., 2026). Under this framework, biochar's porous structure is theorised to provide additional colonisable surface area for fibrolytic bacteria, promoting microbial stability and buffering rumen pH within a range favourable to cellulolytic activity (Chang et al., 2026). Improved microbial colonisation and stability, in turn, are expected to translate into greater substrate degradation and higher cumulative gas production during in vitro incubation, providing the theoretical basis for the gas production technique adopted as the principal digestibility indicator in this study.

Empirical Literature Review

Nutritional Characteristics of Tannin-Rich Browse Species

Indigenous browse species remain important dry-season feed resources for small ruminants because of their comparatively high crude protein content relative to senescent grasses. Agolisi et al. (2020), Tabu et al. (2025) and Tura et al. (2024) reported crude protein concentrations of 12% to 22% dry matter (DM) across a range of browse species, comfortably above the 7-8% threshold required to sustain rumen microbial activity, although Tabu et al. (2025) and Tura et al. (2024) observed that seasonal maturity substantially reduced nutritional quality through increased lignification. Andrade et al. (2022) and Guo et al. (2024) similarly reported neutral detergent fibre (NDF) and acid detergent fibre (ADF) concentrations sufficiently high to constrain digestibility and voluntary intake in several browse species. These findings indicate that crude protein content alone is an unreliable predictor of feeding value, since digestibility is jointly determined by structural carbohydrate content and anti-nutritional compound concentration.

Mechanisms and Effects of Condensed Tannins on Digestibility

Numerous in vitro and in vivo studies confirm that high condensed tannin concentrations depress ruminant digestibility. Valcl and Lavrenčič (2025), Kellali et al. (2026) and Rossi et al. (2022) reported reductions in dry matter digestibility of 10% to 25% in tannin-rich diets relative to low-tannin controls, attributing the decline to impaired microbial degradation following tannin-protein and tannin-fibre complexation. In lactating goats specifically, Battelli et al. (2024) reported that graded inclusion of purified quebracho condensed tannin extract (2%, 4% and 6% of dietary DM) produced a linear decline in total-tract digestibility of up to 11%, while dry matter intake remained largely unaffected, demonstrating that the digestibility penalty of condensed tannins can operate independently of any reduction in voluntary consumption. Ingold et al. (2023), working with Batinah goat bucks in Oman, similarly found that a commercial tannin feed additive reduced diet digestibility relative to untreated controls, reinforcing the consistency of this inhibitory effect across tannin sources and goat production systems. Consistent with the tannin-protein complexation theory outlined above, these findings collectively establish condensed tannins as the principal anti-nutritional constraint limiting the effective utilization of browse-based diets.

In Vitro Gas Production as a Digestibility Assessment Technique

The in vitro gas production technique is widely used to characterise fermentation kinetics because cumulative gas volume reflects the extent and rate of microbial substrate degradation under standardised, controlled conditions (Santos-Sánchez et al., 2024). Pautong et al. (2022) demonstrated that combining gas production measurement with direct dry matter and organic matter digestibility assays provides a more comprehensive characterisation of feed degradability than either method applied in isolation, an approach adopted in the present study. Duijsens et al. (2022) cautioned, however, that in vitro systems cannot fully replicate the complexity of in vivo rumen digestion, since they exclude feed selection behaviour, passage rate and host physiological responses, meaning that in vitro results should be interpreted as indicative of fermentation potential rather than a direct proxy for animal performance.

Biochar as a Tannin Mitigation Strategy

Evidence on biochar's effectiveness as a tannin-mitigation feed additive remains mixed but generally favourable at moderate inclusion levels. Ayeneshet and Tenaw (2025), synthesising evidence across fattening bulls, dairy cows, layers, broilers, pigs, goats and sheep, reported that biochar supplementation is associated with improved feed digestibility, growth performance and reduced enteric methane output, while a meta-analysis published in the Czech Journal of Animal Science found that biochar supplementation significantly increased dry matter, organic matter, crude protein and neutral detergent fibre digestibility across pooled in vitro and in vivo datasets. Qomariyah et al. (2023) similarly found that biochar inclusion between 1% and 3% of dietary dry matter improved digestibility parameters and microbial efficiency, a dose range consistent with the levels evaluated in this study.

Not all evidence points in the same direction. Dittmann et al. (2024), in a controlled crossover trial with lactating dairy cows, found that 1% dietary biochar had no significant effect on feed intake, milk yield or nutrient digestibility, while Lind et al. (2024) reported that biochar supplementation in lambs stimulated short-chain fatty acid production in vitro without a corresponding change in growth rate, and that dry matter intake was affected at low and medium, but not high, biochar inclusion levels. These inconsistencies have been attributed to differences in biochar feedstock, pyrolysis temperature, particle size, inclusion rate, basal diet composition and animal species (Mokhtarpour, 2025). Limited in vitro research, however, has specifically evaluated biochar's effectiveness against the browse species relied upon by Galla goats in Kenya's ASALs, representing the empirical gap addressed in this article.

Summary of Research Gaps

The reviewed literature demonstrates reasonably strong consensus that condensed tannins depress ruminant digestibility and that biochar supplementation can, under favourable conditions, mitigate this constraint. However, three gaps remain evident. First, most existing biochar-digestibility evidence derives from temperate livestock systems and standard forage or concentrate diets, with comparatively little research conducted on the specific tannin-rich indigenous browse species that dominate Kenyan ASAL feeding systems. Second, where digestibility responses to biochar have been reported, few studies have systematically compared the response across multiple browse species differing in tannin burden within a single standardised experimental framework, limiting the ability to draw species-specific inclusion-level recommendations. Third, existing dose-response evidence is inconsistent regarding whether digestibility improves linearly or curvilinearly with biochar inclusion, a question with direct practical relevance for determining a cost-effective recommended inclusion level. This article addresses these gaps by evaluating four graded biochar inclusion levels against four browse species differing substantially in condensed tannin concentration under standardised in vitro conditions.

Conceptual Framework

The conceptual framework linking the study variables is structured as a causal pathway in which biochar inclusion level (0%, 1%, 2% and 3% of feed dry matter), the independent variable, is hypothesised to influence in vitro digestibility, operationalised through cumulative gas production, dry matter degradability and organic matter degradability, the dependent variables. Condensed tannin concentration, which varies by browse species, is treated as a moderating factor that determines the baseline severity of the digestibility constraint that biochar is expected to mitigate. The framework proposes that biochar adsorbs part of the tannin fraction present in each browse species, reducing the formation of inhibitory tannin-protein and tannin-fibre complexes and thereby increasing the substrate available for microbial fermentation, which is reflected in higher cumulative gas production and degradability coefficients at moderate inclusion levels.

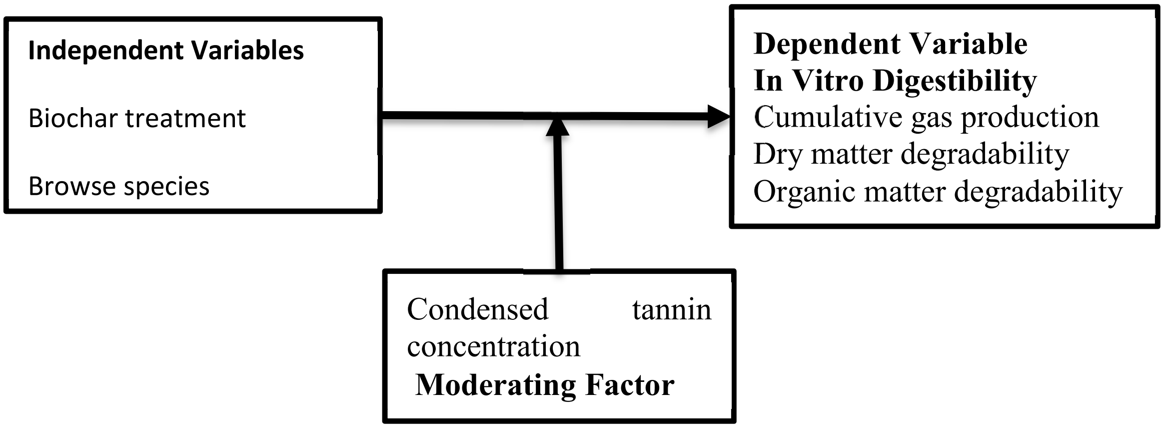

Figure 1: Conceptual Framework

Research Design

The in vitro digestibility trial was arranged as a Completely Randomized Design (CRD). This design was considered appropriate because all experimental units, calibrated glass syringes, were subjected to identical laboratory conditions of incubation temperature, inoculum preparation and fermentation environment, leaving no identifiable source of variation requiring blocking. Each of the four browse species was evaluated independently, with four dietary treatments (0%, 1%, 2% and 3% biochar inclusion) replicated four times, giving sixteen experimental units per species.

Study Site and Experimental Material

The study was conducted at Tharaka University Farm, Tharaka-Nithi County, Kenya, an area representative of the drylands in which Galla goats and the four evaluated browse species, Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata, are commonly found. Rhodes grass (Chloris gayana) was used as the basal reference forage in the wider study. Biochar was produced from locally available biomass materials, consistent with the study's emphasis on a low-cost, locally producible intervention suited to pastoral production systems.

Sample Preparation

Dried samples of each browse species, in both untreated and biochar-treated forms, were ground using a laboratory mill to pass through a 1 mm sieve and thoroughly mixed to obtain homogeneous samples. Exactly 350 mg of each sample (dry matter basis) was weighed using a calibrated analytical balance (±0.001 g) and transferred into labelled 100 ml glass syringes, with each treatment prepared in triplicate.

Rumen Fluid Collection

Rumen fluid was collected from a healthy adult donor goat maintained on a diet similar to the experimental feeds, using a flexible stomach tube under hygienic, anaerobic conditions before morning feeding. Approximately 500-700 ml of rumen liquor was collected, with the initial portion discarded to minimise saliva contamination, filtered through four layers of sterile cheesecloth into pre-warmed flasks continuously flushed with carbon dioxide, maintained at approximately 39°C, and transported immediately to the laboratory for incubation.

In Vitro Incubation Procedure

A buffered rumen inoculum was prepared by mixing rumen fluid with mineral buffer solution in a 1:2 ratio (v/v) under continuous carbon dioxide flushing. Exactly 30 ml of buffered inoculum was dispensed into each syringe containing 350 mg of feed sample, sealed and incubated in a thermostatically controlled water bath at 39°C for 96 hours. Cumulative gas production was recorded at 3, 6, 12, 24, 48, 72 and 96 hours without interrupting incubation, with blank syringes containing inoculum alone included to correct for gas production originating from the inoculum itself. Following incubation, fermentation residues were oven-dried at 105°C for 24 hours to determine dry matter degradability, and combusted in a muffle furnace at 550°C for 4 hours to determine organic matter degradability.

Gas Production and Degradability Models

Gas production data were fitted to the exponential model of Ørskov and McDonald, $Y = a + b(1 - e^{-ct})$, where Y is cumulative gas production at time t (ml), a is the gas produced from the immediately soluble fraction, b is the gas produced from the insoluble but degradable fraction, and c is the fractional rate constant of degradation per hour. Potential degradability was estimated as a + b. Dry matter degradability (DMD) and organic matter degradability (OMD) were each computed as the proportional loss between the initial sample weight (or organic matter content) and the corresponding residue weight (or organic matter content) after incubation, expressed as a percentage.

Data Analysis

Data were analysed using the Statistical Analysis System (SAS, version 9.0). Treatment means for cumulative gas production at each incubation time point, condensed tannin concentration and degradability parameters were subjected to one-way Analysis of Variance (ANOVA), with significant means separated using Tukey's Honestly Significant Difference (HSD) test at the 5% significance level ($P < 0.05$).

RESULTS AND DISCUSSION

The in vitro digestibility component of the study comprised 64 planned observations across the four browse species, biochar levels and replicates, all of which were successfully completed (100% completion rate). Gas production increased progressively with incubation time across all treatments and species, with the magnitude and statistical significance of biochar treatment effects becoming more pronounced as fermentation progressed.

4.1.1 Cumulative Gas Production of Balanites aegyptiaca

Biochar Level	**3 h**	**6 h**	**12 h**	**24 h**	**48 h**	**72 h**	**96 h**
0%	3.25	6.97	12.48	19.42	27.80	34.25	37.85
1%	3.39	7.68	13.74	21.04	30.66	37.81	42.36
2%	4.28	8.14	15.33	23.28	33.57	40.68	44.07
3%	3.16	8.05	14.70	22.96	32.75	39.31	43.11
SEM	0.35	0.40	0.31	0.26	0.34	0.32	0.35
P-value	0.140	0.212	<0.001	<0.001	<0.001	<0.001	<0.001

Note. Gas production expressed in ml. Treatment differences were evaluated using one-way ANOVA at each incubation time, with $P < 0.05$ considered statistically significant.

Cumulative gas production for Balanites aegyptiaca increased with incubation time across all treatments. The treatment effect was not statistically significant during the early fermentation phase ($P = 0.140$ at 3 hours; $P = 0.212$ at 6 hours) but became highly significant from 12 hours onward ($P < 0.001$). At 96 hours, the 2% biochar treatment recorded the highest gas production at 44.07 ml, approximately 16.4% higher than the untreated control (37.85 ml), followed by 3% (43.11 ml) and 1% (42.36 ml). The pattern is consistent with the tannin-protein complexation theory: tannins present in untreated Balanites aegyptiaca are theorised to bind dietary protein and interfere with fibrolytic enzyme activity, while biochar's adsorption of part of the tannin fraction plausibly restored greater substrate availability during the later, more fibre-dependent phase of fermentation. This interpretation is consistent with Besharati et al. (2022) and Tong et al. (2022), who linked high tannin concentrations to reduced microbial activity, and with recent evidence that biochar can enhance rumen fermentation under favourable dosing conditions (Ayeneshet & Tenaw, 2025). The decline observed at 3% relative to 2% biochar reinforces the adsorption theory's prediction of diminishing marginal returns beyond an optimal inclusion threshold, a pattern also reported by Qomariyah et al. (2023).

4.1.2 Cumulative Gas Production of Berchemia discolor

Biochar Level	**3 h**	**6 h**	**12 h**	**24 h**	**48 h**	**72 h**	**96 h**
0%	5.07	8.54	15.37	22.28	32.15	39.46	43.61
1%	5.12	9.19	16.43	25.03	34.75	41.95	46.08
2%	4.66	10.15	17.71	27.26	36.85	44.79	48.88
3%	5.10	10.42	17.38	25.80	35.46	43.03	47.14
SEM	0.45	0.29	0.31	0.32	0.28	0.43	0.38
P-value	0.867	0.002	0.001	<0.001	<0.001	<0.001	<0.001

Note. Gas production expressed in ml. Treatment differences were evaluated using one-way ANOVA at each incubation time, with P < 0.05 considered statistically significant.

Gas production for Berchemia discolor followed a similar time-dependent pattern, with no significant treatment effect at 3 hours (P = 0.867) but significant differences emerging from 6 hours (P = 0.002) and remaining highly significant through 96 hours (P < 0.001). The 2% biochar treatment again recorded the highest cumulative gas production at 96 hours (48.88 ml), approximately 12.1% higher than the control (43.61 ml). Berchemia discolor recorded the second-lowest condensed tannin concentration among the four species evaluated (Section 4.5), which may partly explain why its proportional response to biochar treatment, while still significant, was comparatively modest relative to the higher-tannin species discussed below. This is consistent with the theoretical expectation that biochar's mitigating effect should scale, to some extent, with the severity of the underlying tannin constraint.

4.1.3 Cumulative Gas Production of Acacia tortilis

Biochar Level	**3 h**	**6 h**	**12 h**	**24 h**	**48 h**	**72 h**	**96 h**
0%	3.27	6.04	10.88	16.81	24.46	31.34	34.96
1%	3.19	6.45	12.38	19.30	28.21	34.60	37.70
2%	3.53	7.67	13.71	20.88	30.24	36.15	41.23
3%	3.30	6.84	13.12	19.99	29.05	35.48	39.68
SEM	0.32	0.36	0.27	0.36	0.33	0.28	0.39
P-value	0.886	0.040	<0.001	<0.001	<0.001	<0.001	<0.001

Note. Gas production expressed in ml. Treatment differences were evaluated using one-way ANOVA at each incubation time, with P < 0.05 considered statistically significant.

Acacia tortilis, the species recording the highest condensed tannin concentration of the four evaluated (Section 4.5), showed no significant treatment effect at 3 hours (P = 0.886) but a significant difference emerged from 6 hours (P = 0.040), strengthening progressively through 96 hours (P < 0.001). At 96 hours, the 2% biochar treatment produced 41.23 ml, an increase of approximately 17.9% over the control (34.96 ml), the largest proportional improvement recorded among the four species. This finding is notable because it aligns closely with the theoretical prediction that biochar's mitigating benefit should be most pronounced in the browse species carrying the heaviest tannin burden. The result is consistent with Battelli et al. (2024) and Ingold et al. (2023), both of whom documented digestibility penalties scaling with condensed tannin dose in goats, and supports the interpretation that biochar's adsorption capacity provided proportionally greater relief where tannin-related inhibition was most severe.

4.1.4 Cumulative Gas Production of Zizyphus mucronata

Biochar Level	3 h	6 h	12 h	24 h	48 h	72 h	96 h
0%	4.51	8.04	13.15	20.05	29.39	36.52	40.30
1%	4.42	8.95	14.72	22.35	32.09	39.30	43.16
2%	5.37	9.87	16.05	24.97	35.03	41.92	46.49
3%	4.81	9.27	15.40	23.50	33.66	41.15	44.93
SEM	0.40	0.33	0.36	0.33	0.29	0.32	0.28
P-value	0.378	0.013	0.001	<0.001	<0.001	<0.001	<0.001

Note. Gas production expressed in ml. Treatment differences were evaluated using one-way ANOVA at each incubation time, with P < 0.05 considered statistically significant.

Zizyphus mucronata, the species with the lowest condensed tannin concentration among those evaluated, nonetheless showed a significant biochar treatment effect from 6 hours onward (P = 0.013), reaching a 96-hour peak of 46.49 ml at 2% biochar, approximately 15.4% above the control (40.30 ml). The persistence of a significant, if comparatively modest, biochar response even in the lowest-tannin species suggests that biochar's benefit is not confined to tannin adsorption alone; its porous structure may also enhance microbial attachment and fermentation efficiency independent of tannin content, consistent with the rumen microbial ecology theory outlined in Section 2.1.3.

4.1.5 Condensed Tannin Concentration of Experimental Browse Species

Browse Species	Mean (mg CE/g DM)	SEM	Significance Group
Acacia tortilis	61.83	0.63	d
Balanites aegyptiaca	54.72	0.58	c
Berchemia discolor	38.46	0.38	b
Zizyphus mucronata	31.57	0.43	a

Note. CE = catechin equivalents; DM = dry matter; SEM = standard error of the mean. Means with different superscript letters differ significantly at P < 0.05 (P < 0.001 overall).

The four browse species differed significantly in condensed tannin concentration (P < 0.001), ranging from 31.57 mg CE/g DM in Zizyphus mucronata to 61.83 mg CE/g DM in Acacia tortilis, a difference of 30.26 mg CE/g DM. Notably, Acacia tortilis also recorded the highest crude protein concentration among the browse species evaluated in the wider study, illustrating that crude protein content alone is an unreliable indicator of effective feeding value where substantial anti-nutritional compound concentrations are also present (Osuga et al., 2018). This species-specific tannin gradient provides the empirical foundation for interpreting the differential magnitude of biochar response reported in Sections 4.1 to 4.4, and is broadly consistent with earlier Kenyan evidence documenting considerable inter-species variation in condensed tannin concentration among browse resources used to supplement Rhodes grass diets for small ruminants (Kemboi et al., 2017).

4.1.6 Dry Matter and Organic Matter Degradability Across Biochar Levels

Response Variable	0%	1%	2%	3%	Best-Performing Level	P-value
Cumulative gas production (ml, pooled)	42.8	46.5	50.7	48.9	2%	<0.001
Dry matter degradability, DMD (%)	61.4	64.8	68.2	66.5	2%	<0.001
Organic matter degradability, OMD (%)	58.7	62.1	65.6	63.8	2%	<0.001

Note. Values are pooled means across the four browse species evaluated under Objective One.

The pooled degradability data reinforce the pattern observed within individual species. Dry matter degradability rose from 61.4% under the untreated control to a peak of 68.2% at 2% biochar, a proportional improvement of approximately 11.1%, before declining to 66.5% at 3% inclusion. Organic matter degradability followed an almost identical trajectory, increasing from 58.7% to 65.6% at 2% biochar before declining to 63.8% at 3%. The consistency between the gas production, dry matter degradability and organic matter degradability results across all four measures strengthens confidence that the observed response reflects a genuine improvement in substrate fermentability rather than measurement artefact specific to any single technique, consistent with the recommendation of Pautong et al. (2022) that gas production and direct degradability assays be combined for a more robust digestibility assessment.

DISCUSSION OF FINDINGS

Taken together, the results support rejection of the null hypothesis that biochar treatment has no effect on the in vitro digestibility of the four browse species: cumulative gas production, dry matter degradability and organic matter degradability all differed significantly among biochar levels (P <

0.001) from the mid-fermentation phase onward. The consistent emergence of 2% biochar as the best-performing inclusion level across all four species and both degradability measures, together with the decline observed at 3%, indicates a curvilinear rather than linear dose-response relationship. This pattern is consistent with the adsorption theory's prediction of a threshold beyond which additional biochar yields diminishing or even reversing benefit, plausibly because excess biochar dilutes dietary energy density or interferes with substrate accessibility (Waheed et al., 2026).

The findings also align with, and extend, the broader international evidence on biochar as a ruminant feed additive. A recent meta-analysis in the Czech Journal of Animal Science similarly reported significant improvements in dry matter, organic matter and fibre digestibility following biochar supplementation across pooled in vitro and in vivo datasets, while Ayeneshet and Tenaw (2025) documented comparable digestibility gains across multiple livestock species. At the same time, the present findings are more consistent than some recent evidence from temperate systems: Dittmann et al. (2024) reported no significant digestibility improvement from 1% biochar in lactating dairy cows fed conventional total mixed rations, and Lind et al. (2024) found inconsistent intake responses in lambs across biochar inclusion levels. A plausible explanation for this divergence is that biochar's adsorption mechanism confers the greatest relative benefit where a substantial anti-nutritional constraint, such as the condensed tannins present in tropical browse, is already present to be mitigated; in low-tannin, conventional forage or concentrate diets, there may simply be less inhibitory substrate for biochar to neutralise. This interpretation is reinforced by the observation, in Section 4.5, that Acacia tortilis, the highest-tannin species, recorded the largest proportional gas production improvement (17.9%) of the four species evaluated.

The species-specific variation in response magnitude also carries a practical implication distinct from the pooled treatment averages: uniform biochar inclusion recommendations applied indiscriminately across browse species may under-serve high-tannin species such as Acacia tortilis while potentially over-supplementing lower-tannin species such as Zizyphus mucronata. This nuance is consistent with the summary of research gaps in Section 2.3, which noted the scarcity of species-differentiated dose-response evidence for browse-based diets, and represents a contribution of the present findings beyond the pooled, single-species evidence that dominates much of the existing biochar literature.

Comparison with International and Regional Studies

The 10% to 25% digestibility reductions attributable to high condensed tannin concentrations reported by Valcl and Lavrenčič (2025), Kellali et al. (2026) and Rossi et al. (2022) provide a useful benchmark against which to interpret the magnitude of the untreated-control deficits observed in this study; the 11.1% and 10.5% proportional gains in dry matter and organic matter degradability, respectively, recorded between the 0% and 2% biochar treatments fall broadly within, albeit toward the lower end of, this reported range, consistent with a partial rather than complete mitigation of the underlying tannin constraint. The finding that biochar improved fermentation without eliminating the tannin effect entirely is consistent with Battelli et al. (2024), who reported that even substantial condensed tannin mitigation strategies in dairy goats typically achieve partial rather than complete restoration of digestibility. Within the Kenyan and East African context specifically, the results extend the earlier browse-characterisation work of Kemboi et al. (2017), which documented considerable inter-species variation in condensed tannin concentration among indigenous browse species but did not evaluate biochar or any comparable mitigation strategy, positioning the present study as a direct empirical response to that identified gap.

Conclusion

This article set out to determine the effect of biochar treatment on the in vitro digestibility of Balanites aegyptiaca, Berchemia discolor, Acacia tortilis and Zizyphus mucronata, four tannin-rich browse species central to Galla goat feeding systems in Kenya's arid and semi-arid lands. Biochar supplementation significantly improved cumulative gas production, dry matter degradability and organic matter degradability across all four species, with treatment effects becoming statistically significant from the mid-fermentation phase onward and strengthening through 96 hours of incubation. Moderate biochar inclusion, at approximately 2% of dietary dry matter, consistently produced the most favourable fermentation and degradability response, while inclusion at 3% did not sustain this advantage, confirming a curvilinear rather than linear dose-response relationship. The magnitude of improvement varied by browse species, with the highest-tannin species, Acacia tortilis, recording the largest proportional gain, suggesting that biochar's mitigating benefit scales with the severity of the underlying tannin constraint. The study concludes that biochar, produced from locally available biomass, demonstrates clear potential as a practical, low-cost treatment for improving the utilization of tannin-rich browse resources in Kenyan dryland goat production systems, thereby rejecting the null hypothesis that biochar treatment has no effect on the in vitro digestibility of the evaluated browse species.

Recommendations

i. **Livestock nutritionists and feed formulators** should recommend biochar inclusion at approximately 2% of dietary dry matter when formulating browse-based supplementary diets for goats in ASAL production systems, since this level consistently produced the most favourable digestibility response across all four species evaluated.
ii. **Livestock extension officers** should provide pastoral households with practical guidance on producing and applying biochar from locally available biomass, given its demonstrated potential as a low-cost alternative to costly external concentrate supplementation.
iii. **Farmers and feed formulators** should avoid assuming that higher biochar inclusion automatically improves feed utilization; the decline in fermentation and degradability observed at 3% inclusion indicates that excessive biochar supplementation may not provide additional benefit and could unnecessarily raise input costs.

iv. **Feed formulators** should consider species-specific tannin concentration when recommending biochar inclusion levels, since browse species carrying a heavier tannin burden, such as Acacia tortilis, appear to derive proportionally greater benefit from biochar treatment than lower-tannin species such as Zizyphus mucronata.

Suggestions for Further Research

The findings are based on in vitro fermentation data and therefore cannot fully capture in vivo factors such as feed selection behaviour, passage rate and host physiological response, a limitation acknowledged in the broader in vitro methodology literature (Duijsens et al., 2022). Further research should validate the in vitro findings reported here through in vivo feeding trials measuring feed intake, nutrient digestibility and milk yield in lactating Galla goats fed biochar-treated browse. Future studies should also investigate the relationship between biochar feedstock source, pyrolysis temperature and the magnitude of digestibility improvement, since this study evaluated a single locally produced biochar type, and examine whether the species-specific response gradient identified in this study, wherein higher-tannin species showed proportionally greater biochar benefit, holds across a broader range of browse species and tannin concentrations.

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