Research Article

Quantifying the Effects of Forage Chop Length on Silage Characteristics, Digestive Responses, and Productivity in Ruminants: A Meta-Analysis

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Abstract | Although forage chop length is widely recognized as a factor influencing animal performance, it remains unclear whether it independently accounts for observed changes in animal responses or occurs through interactions with other feeding strategies. This meta-analysis synthesized data from 61 peer-reviewed articles to examine the effects of forage chop length variation on silage characteristics, ruminal fermentation, nutrient digestibility, and ruminant productivity, using random-effects models. The results showed that reducing chop length significantly increased silage dry matter (DM) content (Estimate = 0.87; 95% CI: 0.24 to 1.49; P < 0.01) and reduced DM losses (Estimate = -0.40; 95% CI: -0.70 to -0.20; P < 0.05). Regarding animal performance, reduction in particle size was associated with a significant increase in dry matter intake (DMI; Estimate = 0.42 kg/d; 95% CI: 0.02 to 0.81; P < 0.05) and total DM digestibility (Estimate = 0.64%; 95% CI: 0.20 to 1.09; P < 0.01). Body weight gain also significantly improved (Estimate = 1.85 kg; 95% CI: 1.11 to 2.58; P < 0.01). Milk yield showed a tendency to rise (Estimate = 0.18 kg/d; 95% CI: -0.01 to 0.36; P = 0.06), although this was accompanied by a significant reduction in milk fat content (Estimate = -0.28%; 95% CI: -0.55 to 0.00; P < 0.05). Critical interpretation of these findings is required, as high heterogeneity was observed for most outcomes, including silage DM (I2 = 92.70%), DMI (I2 = 83.22%), and body weight gain (I2 = 93.34%). These metrics indicate that results are highly inconsistent across studies. Consequently, optimizing forage chop length represents a practical strategy for improving silage quality and nutrient utilization. However, its effectiveness depends on forage characteristics, diet composition, and management practices. Therefore, species- and production system-specific recommendations are required to maximize the nutritional and productive benefits of optimizing chop length.

Keywords | Particle size reduction, Physically effective fiber, Feed processing intensity, Chewing activity, Rumen function

Received | September 27, 2026; **Accepted** | August 09, 2026; **Published** | August 21, 2026
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Citation | Ridla M, Albarki HR, Risyahadi ST, Daulai MS, Adawiyah DR, Kusuma RI (2026). Quantifying the effects of forage chop length on silage characteristics, digestive responses, and productivity in ruminants: A meta-analysis. Adv. Anim. Vet. Sci., 14(9):1991-2005.
DOI | https://dx.doi.org/10.17582/journal.aavs/2026/14.9.1991.2005
ISSN (Online) | 2307-8316

INTRODUCTION

Forage chop length has been identified as a major determinant of the efficiency of nutrient preservation and utilization by ruminants. Meanwhile, silage is an important component of ruminant diets, especially during periods of low fresh forage availability (Cone *et al*., 2008). It is made by anaerobic fermentation of moist forage biomass, which makes up for the nutrients in a stabilized manner and ensures that a steady feed supply is available throughout the year (Kung *et al*., 2018). Among the physical characteristics of forage, chop length plays a very important role in forming the characteristics of silage fermentation, nutrient availability, and feeding behavior, which have a direct effect on animal performance (Krause *et al*., 2002; Izadbakhsh *et al*., 2024). Although forage chop length is recognized as an important management factor influencing silage quality and animal performance, the optimal chop length remains controversial because reported responses vary with forage species, ensiling conditions, and feeding management strategies.

While the effects of chop length are well-documented in individual studies, published findings remain inconsistent, and a significant quantitative gap exists in identifying universal responses across diverse conditions. Some studies have reported an increase in dry matter intake (DMI) and elevated ruminal pH with shorter chop lengths, while others have found reduced ruminal pH and acetate to propionate ratios (Bhandari *et al*., 2007; Tayyab *et al*., 2019). This meta-analysis addresses this gap by moving beyond qualitative summaries to provide novel quantitative estimates. By synthesizing evidence from 61 peer-reviewed articles, we can answer questions regarding the magnitude of response that individual, often contradictory, trials cannot resolve alone.

To guide our evaluation, we established several a priori hypotheses based on established nutritional principles, including Silage Preservation: We hypothesized that shorter chop lengths would improve silage quality by creating more surface area for microbial activity, resulting in a faster rate of pH reduction and reduced dry matter (DM) loss during ensiling (Addah *et al*., 2016). Rumen Dynamics: We expected that while finely chopped forage would increase the passage rate, potentially restricting microbial attachment, it would be offset by an expansion in surface area for microbial invasion, thereby shifting fermentation toward propionate production. Intake Thresholds: We hypothesized a non-linear response for DMI; moderately chopped forage would be most acceptable, while extremely short particles might reduce silage porosity and DMI, and extremely long particles would reduce voluntary intake by increasing chewing time (Addah *et al*., 2016). Production Trade-offs: A critical hypothesis was the existence of a physiological trade-off; shorter chop lengths would enhance energy availability and milk yield but simultaneously decrease the intake of physically effective neutral detergent fiber (peNDF), leading to reduced ruminal buffering and a subsequent reduction in milk fat concentration (Yang and Beauchemin, 2009; McDonald *et al*., 2011).

Reconciling the discrepancies among published studies requires considering the interaction between forage particle size, diet composition, and feeding management practices. For example, although shorter chop lengths may reduce fiber digestibility in some situations, this response can be partially compensated by the greater dry matter intake (DMI) observed with finer particle sizes, resulting in similar or even greater overall nutrient intake (Bhandari *et al*., 2008; Randby *et al*., 2024). However, excessively fine particles may increase the risk of subacute ruminal acidosis (SARA), particularly in high-producing dairy cows receiving high-concentrate diets, due to reduced physically effective neutral detergent fiber (peNDF), lower chewing activity, and decreased salivary buffering capacity. Therefore, maintaining adequate peNDF remains essential for preserving ruminal stability and supporting milk fat synthesis (Zebeli *et al*., 2012).

This study intentionally integrates data from dairy, beef, and small ruminant systems to determine if universal biological principles of particle size reduction apply across different metabolic requirements. While we acknowledge that dairy cows, beef steers, and sheep have fundamentally different nutritional priorities, a holistic meta-analytical approach allows us to identify whether chop length serves as a consistent tool or if its effects are strictly system-specific. Therefore, this meta-analysis aimed to quantitatively evaluate how forage chop length influences silage quality, ruminal fermentation, nutrient digestibility, and ruminant performance across these diverse production systems.

MATERIALS AND METHODS

Database development

The database was compiled from peer-reviewed articles investigating the influence of forage chop length on silage properties and animal performance. Sources were identified using English-language keywords such as "chop," "silage," and "particle size," and searches were conducted in Scopus and ScienceDirect. While acknowledging that additional databases like Web of Science or CAB Abstracts exist, Scopus and ScienceDirect were specifically selected for their broad coverage of peer-reviewed animal science literature, ensuring a high standard of data quality for effect size calculations. The search yielded a substantial initial pool of 3,931 records, and the final database was completed in October 2025.

The selection framework followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Liberati *et al*., 2009). As described in Figure 1, the initial search results from 35 years (1990–2024) were screened. After title screening and eliminating reviews and conference papers, which often lack the standardized quantitative data (means and standard deviations) required for calculating Hedges' g, a total of 3,849 publications were excluded. The remaining 82 studies were screened in full text by a curation team including (Ridla*et al*., 2024) with disagreements resolved through consensus. Among these, 21 were excluded due to an absence of controls, differing outcomes, or being inadequate in providing quantitative information. Ultimately, 61 studies met the inclusion criteria for meta-analysis, encompassing a diverse range of chop lengths (1.18 mm to 152 mm), forage types (grass, legume, and by products), and animal species including dairy cows, beef steers, sheep, and goats. This holistic approach was intentionally chosen to identify if universal biological principles of particle size reduction apply across different metabolic requirements and production systems.

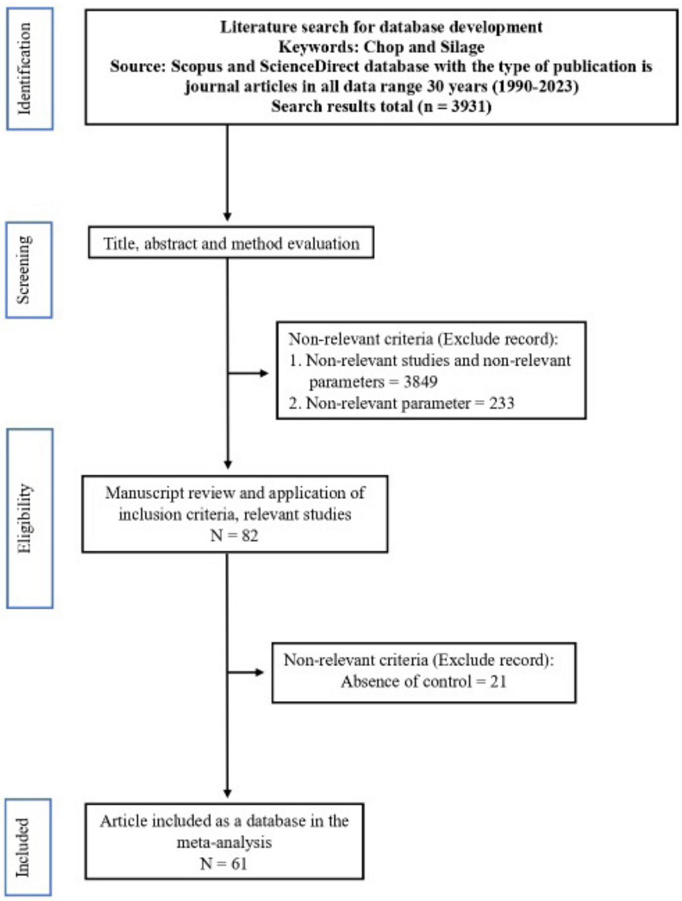

Figure 1: Flow chart of the article selection process based on Preferred Reporting Items for systematic (PRISMA) reviews and meta-analysis protocol.

Data extraction

Methodological quality and risk of bias were assessed during the extraction phase; studies were included only if they provided the quantitative parameters (means, sample sizes, and standard deviations/errors) necessary for effect size determination. The statistical approach followed a random-effects model, consistent with the method used by Ridla *et al*. (2025). This model was specifically selected to accommodate the true between-study variance (**vi**) expected in a meta-analysis involving diverse experimental designs and livestock species, rather than assuming a single fixed effect.

The primary formula, based on Sánchez-Meca and Marín-Martínez (2010) and Cheung and Vijayakumar (2016), is expressed as:

$$y_i = \theta + u_i + e_i$$

Here, y_i represents the observed effect size (Hedges' g) for the i^{th} comparison, θ denotes the overall mean effect size, u_i is the between-study random effect, and e_i is the within-study sampling error.

Effect sizes were calculated as Hedges' g, which corrects Cohen's standardized mean difference for small-sample bias. Cohen's d was first calculated as:

$$d = \frac{\bar{X}_E - \bar{X}_C}{S_p}$$

Where; $\bar{X}E$ and $\bar{X}c$ are the mean responses of the experimental (short chop) and control (long chop) groups, respectively, and S_p is the pooled standard deviation.

The pooled standard deviation was calculated as:

$$S_p = \sqrt{\frac{(N_E - 1)S_E^2 + (N_C - 1)S_C^2}{N_E + N_C - 2}}$$

Where; N_E and N_c denote the sample sizes of the experimental and control groups, respectively, and S_E and S_C represent their corresponding standard deviations.

Hedges' g was then obtained by applying the small-sample correction factor:

$$g = J \times d$$

Where;

$$J = 1 - \frac{3}{4(N_E + N_C - 2) - 1}$$

and J is the correction factor for small sample sizes.

To accommodate the effect of variability between studies, the estimation of the variance component (τ^2) was done using the method of DerSimonian and Laird (1986):

$$\tau^2 = (Q - df)/ C$$

Where Q is the Cochran Q statistic, degrees of freedom are df, and C is a scaling constant.

Although more advanced approaches for assessing publication bias are available, Rosenthal's fail-safe number (Nfs) was employed as an indicator of the robustness of the meta-analysis. The pooled results were considered robust when the fail-safe number exceeded the criterion of 5N + 10, where N denotes the number of studies included in the analysis (Rosenthal, 1979).

All meta-analytical computations, including the evaluation of between-study heterogeneity, were conducted with the OpenMEE software package (Wallace *et al*., 2016), focusing on outcome variables related to feed quality, intake, fermentation, and performance. Furthermore, a data-driven meta-regression was performed specifically for DMI to quantify the impact of specific particle size changes, recognizing it as a main determinant of animal performance.

RESULTS

Published studies were compiled into a comprehensive meta-database to evaluate the effects of forage chop length using descriptive statistics to summarize the nature of the trials and the response variables, as detailed in Tables 1 and 2. Substantial heterogeneity was observed among studies, likely reflecting differences in experimental design, forage type, chopping intensity, and ensiling conditions. Nevertheless, the robustness analysis demonstrated that the pooled estimates were highly stable. All primary response variables produced fail-safe numbers (Nfs) well above the critical threshold (5N + 10), indicating that the observed effects were unlikely to be substantially influenced by publication bias or the file-drawer problem. Notably, the exceptionally high Nfs values for silage dry matter (2,102) and dry matter intake (756) indicate that these findings would remain statistically significant even in the presence of a large number of unpublished null studies. Similarly, silage ammonia nitrogen (NH_3-N), ruminal pH, the acetate-to-propionate (A:P) ratio, dry matter digestibility (DMD), organic matter digestibility (OMD), dry matter intake (DMI), and body weight gain (BWG) also exhibited high Nfs values, supporting the reliability of the corresponding pooled estimates. In contrast, milk yield, milk fat, and milk protein showed comparatively lower Nfs values, suggesting that these responses should be interpreted with greater caution because they may be more susceptible to the influence of unpublished studies.

Table 1: Literature used in the development of the meta-database.

No	References	Silage materials used	Forage type	Treatment addiction	Storage time (Day)	Chop length (mm)	Animal used
1	Addah *et al*., 2014	Barley	Grass	Uninoculated and inoculated	64 and 294	20 and 10	Beef cattle
2	Addah *et al*., 2015	Barley	Grass	Uninoculated and inoculated	294	20 and 10	Beef cattle
3	Addah *et al*., 2016	Barley	Grass	-	311	20 and 10	Beef cattle
4	Alende *et al*., 2009	Sorghum	Grass	-	90	9.4 and 5.8	Angus cattle
5	Bal *et al*., 2000	Corn	By product	-	21	19, 14.5, and 9.5	Frisian holstein
6	Beauchemin and Yang, 2005	Corn silage	By product	-	120	11.5, 10.3, and 8.9	Frisian holstein
7	Beauchemin *et al*., 1994	Alfalfa	Legume	-	6	10 and 5	Frisian holstein
8	Beauchemin *et al*., 2003	Alfalfa	Legume	-	6	Chopped and ground	Frisian holstein
9	Bhandari *et al*., 2007	Alfalfa and corn	Legume	-	90	19 and 10	Frisian holstein
10	Bhandari *et al*., 2008	Alfalfa and oat	Legume	-	90	19 and 6	Frisian holstein
11	Castle *et al*., 1979	Perennial Ryegrass	Grass	-	30	72, 17.4, and 9.4	Ayshire cows
12	Castle, 1981	Perennial Ryegrass	Grass	Early and Late cut	30	19.5 and 11.6	Ayshire cows
13	Charmley *et al*., 1999	Orchardgrass and white clover	Grass			Chopped and macerated	Hereford and Shorthorn

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No	References	Silage materials used	Forage type	Treatment addiction	Storage time (Day)	Chop length (mm)	Animal used
14	Couderc *et al*., 2006	Corn	By product	-	16	23 and 6	Frisian holstein
15	Deswysen *et al*., 1978	Italian ryegrass	Grass	With and without formic acid	30	53 and 18	Texel sheep
16	Diepersloot *et al*., 2022	Bermuda Grass and Oat	Grass and legume	Bacterial inoculum	30 and 90	65 and 25	-
17	Einarson *et al*., 2004	Barley silage	By product	High concentrate	30	19 and 8	Frisian holstein
18	Fernandez *et al*., 2004a	Corn silage	By product	Early and late harvesting	29	13 and 5	Frisian holstein
19	Fernandez *et al*., 2004b	Corn silage	By product	Mid-early and early hybrid	29	13 and 5	Frisian holstein
20	Ferraretto *et al*., 2015	Corn silage	By product	-	120	19.5 and 6.4	Frisian Holstein cow
21	Fitzgerald, 1996a	Lolium perenne	Grass		30	84, 70, and 29	Suffolk cross-breed lambs
22	Fitzgerald, 1996b	Lolium perenne	Grass	Unwilting and wilting	30	50 and 20	Suffolk cross-breed lambs
23	Fitzgerald, 1996c	Lolium perenne	Grass	-	30	9.1, 11.8, and 6.8	Suffolk cross-breed lambs
24	Fonseca *et al*., 2000	Co silage	By product	-	30	30 and 10	-
25	Gordon, 1982	Lolium perenne	Grass	-	30	47 and 14	Frisian Holstein cow
26	Havekes *et al*. 2020	Corn	By product	-	42	101.6 and 25.4	Frisian Holstein cow
27	Johnson *et al*., 2003	Corn	By product	Mechanical and non-mechanical processing	30	27.8 and 11.1	Frisian Holstein cow
28	Kammes *et al*., 2012	Alfalfa	Legum	-	30	19 and 10	Frisian Holstein cow
29	Kammes and Allen, 2012	Orchardgrass	Grass	-	30	19 and 10	Frisian Holstein cow
30	Kanonoff and Heinrichs, 2003	Corn	By product	TMR + cottonseed hulls	30	11.8 and 8	Frisian Holstein cow
31	Kornfelt, 2013	Alfalfa	Legum	Early and late harvesting	60	>50 and 19	Jersey cows
32	Li *et al*., 2020	Alfalfa	Legum	-	7	19, 8, and 1.18	Frisian Holstein cow
33	Lin *et al*., 2021	Corn Stalk	By product	-	-	80-50 and 20	Frisian Holstein cow
34	Lyimo *et al*., 2018	Elephant grass	Grass	-	60	40 and 20	-
35	McEniry *et al*., 2011	Grass Silage	Grass	Unwilting and wilting	210	-	-
36	Miller *et al*., 1969	Corn silage	By product	-	70	10 and 13	Frisian Holstein cow
37	Moore-Colyer *et al*., 2003	Big-bale grass silage	By product	-	21	53 and 68	Welsh-cross pony geldings
38	O'kiely and Flynn, 1991	Italian ryegrass	Grass	-	135	100 and 50	Herford
39	Onetti *et al*., 2003	Corn	By product	Tallow 0% and Tallow 20%	21	32 and 19	Frisian Holstein cow
40	O-Hernandez *et al*., 1995	Timothy Grass	Grass	-	21	30 and 3	Frisian Holstein cow

Table continues on next page......

Links Researchers

No	References	Silage materials used	Forage type	Treatment addiction	Storage time (Day)	Chop length (mm)	Animal used
41	Randby *et al.*, 2024	Grass-clover silage	Grass	Early cut, low concentrate; late cut, high concentrate	30	152 and 19	Norwegian red dairy cow
42	Randby *et al.*, 2008	Timothy, fescue, red clover	Grass	Early cut and normal cut	30	57 and 24	Norwegian red dairy cow
43	Savoie *et al.*, 1992	Timothy grass	Grass	-	21	47, 37, 21, and 11	Frisian Holstein cow
44	Schwab *et al.*, 2002	Corn	By product	.	28	19 and 13	Frisian Holstein cow
45	Sharifi *et al.*, 2016	Alfalfa silage	By product	-	60	25 and 15	Holstein cows
46	Soita *et al.*, 2000	Barley	By product	Low and high concentrate	27	18.75 and 4.68	Frisian Holstein cow
47	Soita *et al.*, 2003	Barley	-	-	24	18.8 and 4.7	Hereford steers
48	Soita *et al.*, 2005	Corn	-	-	21	19 and 9.5	Frisian Holstein cow
49	Stockdale and Beavis, 1994	Corn	-	-	21	9 and 36	Frisian Holstein cow
50	Stojanovic *et al.*, (2012	Corn	By product	-	30	<1.18, 8-1.18, and 19-8	Frisian Holstein cow
51	Sudweeks *et al.*, 1979	Corn	By product	-	14	0.63	Jersey steers sheep
52	Sun *et al.*, 2019	Ramie Silage	By product	-	60	20 and 10	Liuyang black goat
53	Sun *et al.*, 2021	Ramie Forage	Grass	-	60	10 and 20	Liuyang black goats
54	Tayyab *et al.* 2019	Grass	Grass	-	28	44 and 10	Frisian Holstein cow
55	Thomson *et al.*, 2017a	Alfalfa and corn	Grass	Low and High Alfalfa	60	19 and 14	Frisian Holstein cow
56	Thomson *et al.*, 2017b	Alfalfa and corn	Legum	First cut (low and high concentrate), second cut (low and high concentrate)	21	19 and 14	Frisian Holstein cow
57	Thomson *et al.*, 2018	Alfalfa	Legum	Low concentrate and High concentrate	21	19 and14	Frisian Holstein cow
58	Yang and Beauchemin, 2005	Alfalfa	Legum	Forage: Concentrate ratio (35:65) and (60:40)	30	19 and 8	Frisian Holstein cow
59	Yang and Beauchemin 2004	Corn silage	By product	-	60	7.59 and 6.08	Frisian Holstein cow
60	Yang and Beauchemin, 2005	Alfalfa	Legum	Forage: Concentrate (35:65) and (60:40)	60	19.1 or 7.9	Frisian Holstein cow
61	Zhang *et al.*, 2010	Rice straw	By product	-	45	>500 and 60	Frisian Holstein cow

Indicators of silage composition and fermentation, such as pH, organic acids, water-soluble carbohydrates (WSC), crude protein (CP), and fiber fractions (NDF, ADF), showed high variability. Between-study heterogeneity, evaluated through Q, tau^2, and I^2 metrics, indicated considerable inconsistency for most parameters. For instance, lactic acid concentration (Q = 252.00, $P < 0.01$, I^2 = 86.11%) and organic matter digestibility (Q = 403.77, $P < 0.01$, I^2 = 89.35%) showed high heterogeneity, suggesting that forage type, processing intensity, and ensiling conditions have powerful effects on these outcomes.

Table 2: Descriptive statistics of the meta-database.

Variable	Unit	N	Control				Treatment			
			Max	Min	Mean	St dev	Max	Min	Mean	St dev
Silage quality										
Dry matter (DM)	% DM	99	90.18	20.00	46.81	16.89	92.90	3.38	45.95	22.08
DM Losses	% DM	60	37.10	2.44	11.25	13.19	38.00	2.43	11.82	13.66
WSC	% DM	34	3.60	0.10	2.09	1.21	3.70	0.10	2.22	1.20
pH	-	52	6.20	3.60	4.22	0.52	6.20	3.63	4.18	0.52
Lactic Acid	% DM	36	12.70	0.30	4.73	3.67	13.20	0.39	4.71	3.39
Acetic Acid	% DM	37	6.26	0.39	2.44	0.38	7.80	0.10	2.41	0.42
Propionic Acid	% DM	19	0.81	0.02	0.28	0.03	0.87	0.01	0.28	0.03
Butyric Acid	% DM	15	0.77	0.03	0.19	0.19	0.86	0.01	0.18	0.22
Ammonia (NH_3)	% TN	14	19.80	0.51	7.71	6.30	23.50	0.49	6.16	6.16
Organic matter	% DM	36	95.10	47.40	76.72	2.55	95.10	45.80	76.55	2.55
Ash	% DM	16	16.55	6.20	9.76	0.21	11.80	6.10	9.22	0.26
Crude protein	% DM	75	23.60	5.01	20.93	7.36	27.90	4.34	21.02	7.86
NDF	% DM	72	69.50	1.33	40.91	13.33	70.60	1.360	40.21	13.52
ADF	% DM	63	52.70	17.10	31.43	9.03	54.07	17.30	31.10	9.01
Rumen fermentation dynamics										
pH		31	7.00	5.49	6.29	0.32	6.90	5.49	6.21	0.33
Ammonia (NH_3)	mg/dL	43	28.50	3.70	10.74	4.76	21.50	3.20	10.93	4.41
Lactic acid	mM DM	44	0.37	0.06	0.16	0.10	0.81	0.04	0.20	0.20
Acetic acid (A)	% mol	46	91.80	48.00	61.60	8.81	91.30	47.20	61.80	9.12
Propionic acid (P)	% mol	46	39.20	15.70	24.26	1.24	40.50	15.90	24.75	1.24
A:P	% mol	41	4.22	1.30	2.42	0.05	3.73	1.40	2.29	0.05
Butyric acid	% mol	46	20.50	7.40	12.87	2.43	19.90	6.70	12.80	2.41
Isobutyric acid	% mol	18	1.37	0.73	0.91	0.02	1.39	0.73	0.92	0.02
Valeric acid	% mol	19	2.60	1.30	1.67	0.43	2.24	1.20	1.63	0.41
Isovaleric acid	% mol	18	2.21	0.60	1.13	0.69	2.24	0.60	1.14	0.67
Total VFA	mM DM	43	152.00	72.80	113.09	3.58	151.00	64.00	113.20	3.58
Digestibility										
DMD	%	49	80.80	44.60	67.77	9.02	83.20	48.80	68.74	8.69
OMD	%	44	73.70	44.80	68.80	4.88	75.40	60.90	69.85	3.23
NDFD	%	36	71.90	23.80	50.57	8.14	76.00	35.00	51.89	8.12
ADFD	%	20	66.90	26.70	47.75	9.84	71.20	22.10	48.95	11.74
Milk performance										
Milk yield	kg/d	75	48.50	12.20	31.53	3.19	49.30	12.50	31.83	3.22
Milk fat	%	73	5.10	2.72	3.66	0.45	5.20	2.71	3.64	0.46
Milk protein	%	75	3.60	2.63	3.13	0.17	3.60	2.65	3.13	0.16
Milk lactose	%	23	5.19	4.41	4.68	0.36	5.22	4.43	4.68	0.36
Body performance										
DMI	kg/d	84	46.40	3.83	20.80	7.99	47.80	3.88	21.12	7.85
OMI	kg/d	28	33.90	13.79	21.56	3.77	42.00	13.97	22.14	5.32
ADFI	kg/d	48	5.86	1.13	4.58	1.56	5.59	1.24	4.55	1.40
NDFI	kg/d	48	29.00	3.25	7.87	4.67	29.60	3.30	7.98	4.71
BWG	kg/d	22	2.01	0.36	0.41	0.57	1.95	0.039	0.41	0.57

WSC= Water soluble carbohydrate; TN= Total nitrogen; BWG= Body weight gain; OMI= Organic matter intake; DMI= Dry matter intake DMD= Dry matter digestibility; OMD: Organic matter digestibility; ADFI= ADF intake; NDFI= NDF intake; ADFD= ADF digestibility; NDFD= NDF digestibility.

Table 3: Result of standard meta-analysis.

Variable	Unit	N	Estimate	Lower bound	Upper bound	Std. error	P-Value	Tau^2	Q(df=k)	Het. P-value	I^2	Nfs
Silage quality												
Dry matter (DM)	%	99	0.87	0.24	1.49	0.32	0.01	8.19	1342.93	<0.001	92.70	2102.00
DM Losses	% DM	60	-0.4	-0.7	-0.2	0.18	0.04	2.10	42.06	<0.01	88.11	34.00
WSC	% DM	34	0.76	-0.13	1.66	0.46	0.09	1.84	43.96	<0.001	70.43	60.00
pH		52	-0.23	-0.51	0.05	0.15	0.11	0.53	124.66	< 0.001	61.50	118.00
Lactic Acid	% DM	36	0.37	-0.50	1.24	0.45	0.40	5.05	252.00	< 0.001	86.11	66.00
Acetic Acid	% DM	37	-0.21	-1.24	0.81	0.52	0.68	6.96	301.16	< 0.001	88.05	53.00
Propionic Acid	% DM	19	-0.19	-1.34	0.97	0.59	0.75	5.03	133.54	< 0.001	86.52	0.00
Butyric Acid	% DM	15	0.04	-1.38	1.46	0.72	0.96	5.08	96.65	< 0.001	85.52	0.00
Ammonia (NH_3)	% TN	14	-0.86	-2.38	0.67	0.78	0.27	4.99	86.69	<0.001	85.01	146.00
Organic matter	% DM	16	-0.35	-1.30	0.61	0.49	0.48	2.62	127.95	< 0.001	88.28	21.00
Ash	% DM	36	-0.98	-2.26	0.30	0.65	0.13	9.98	414.81	< 0.001	91.56	4.00
Crude protein	% DM	75	-0.04	-0.46	0.37	0.21	0.84	2.27	521.89	<0.001	85.82	0.00
NDF	% DM	72	-0.22	-0.61	0.16	0.20	0.26	2.09	339.69	<0.001	79.10	80.00
ADF	% DM	63	-0.46	-1.07	0.15	0.31	0.14	4.72	474.80	<0.001	96.94	139.00
Rumen fermentation dynamics												
pH		31	-0.61	-0.98	-0.24	0.19	0.01	0.50	55.61	0.00	46.06	209.00
Ammonia (NH_3)	mg/dL	43	0.22	-0.21	0.65	0.22	0.32	1.46	152.38	<0.001	72.44	10.00
Lactic acid	mM	14	0.42	-0.18	1.02	0.31	0.17	0.87	38.53	<0.001	66.26	16.00
Acetic acid (A)	% mol	46	0.01	-0.26	0.28	0.14	0.95	0.36	77.85	0.00	42.20	0.00
Propionic acid (P)	% mol	46	0.23	-0.14	0.60	0.19	0.23	1.04	132.31	<0.001	65.99	15.00
A:P		11	-1.38	-2.35	-0.41	0.50	0.01	1.97	38.99	<0.001	74.35	95.00
Butyric acid	% mol	46	-0.23	-0.57	0.11	0.17	0.19	0.83	115.99	<0.001	61.20	23.00
Isobutyric acid	% mol	18	0.46	-0.23	1.15	0.35	0.19	1.70	74.13	<0.001	77.07	22.00
Valeric acid	% mol	19	-0.49	-1.13	0.14	0.32	0.13	1.45	69.60	<0.001	74.14	36.00
Isovaleric acid	% mol	18	0.29	-0.31	0.89	0.31	0.34	1.16	58.05	<0.001	70.71	3.00
Total VFA	mM	43	0.27	-0.15	0.69	0.21	0.20	0.00	3.38	0.97	0.00	0.00
Digestibility (D)												
DMD	%	48	0.64	0.20	1.09	0.23	0.01	1.98	331.60	<0.01	85.83	851.00
OMD	%	44	0.51	-0.03	1.05	0.27	0.06	2.78	403.77	<0.01	89.35	578.00
NDFD	%	34	0.05	-0.53	0.63	0.30	0.86	2.25	167.55	<0.01	80.30	0.00
ADFD	%	18	0.32	-0.45	1.09	0.39	0.42	2.15	81.23	<0.01	79.07	10.00
Milk performance												
Milk yield	kg/d	75	0.18	-0.01	0.36	0.09	0.06	0.21	109.24	0.01	32.26	75.00
Milk fat	%	73	-0.28	-0.55	0.00	0.14	0.05	0.88	207.66	<0.01	65.33	73.00
Milk protein	%	75	-0.01	-0.24	0.23	0.12	0.95	0.58	169.10	<0.01	56.24	75.00
Milk lactose	%	23	0.02	-0.25	0.29	0.14	0.89	0.00	3.49	1.00	0.00	23.00
Body performance												
DMI	kg/d	84	0.42	0.02	0.81	0.20	0.04	2.77	494.76	<0.001	83.22	756.00
OMI	kg/d	48	0.57	-0.01	1.15	0.30	0.05	1.88	128.27	<0.001	78.95	129.00
ADFI	kg/d	48	0.41	-0.03	0.84	0.22	0.07	1.74	202.55	<0.001	76.80	154.00
NDFI	kg/d	48	-0.25	-1.40	0.90	0.59	0.67	1.99	27.22	<0.001	74.29	0.00
BWG	kg/d	47	1.85	1.11	2.58	0.38	<0.01	6.02	690.42	<0.01	93.34	172.00

WSC= Water soluble carbohydrate; TN= Total nitrogen; BWG= Body weight gain; OMI= Organic matter intake; DMI= Dry matter intake DMD= Dry matter digestibility; OMD: Organic matter digestibility; ADFI= ADF intake; NDFI= NDF intake; ADFD= ADF digestibility; NDFD= NDF digestibility.

Silage quality and rumen dynamics

Reduction in the length of chop had a significant positive effect on the silage DM content (Estimate= 0.87; 95% CI: 0.24 to 1.49; P < 0.01) and a simultaneous negative effect on DM losses (Estimate = -0.40; 95% CI: -0.7 to -0.2; P < 0.05), as shown in Table 3. These findings serve as indicators of improved packing density and enhanced anaerobic preservation in shorter-chopped silages. However, other fermentation parameters like pH, organic acids, and NH_3 remained largely unchanged, as did overall nutrient composition including CP, NDF, and ADF.

Regarding ruminal dynamics (Table 3), the presence of shorter particles significantly reduced ruminal pH (Estimate = -0.61; 95% CI: -0.98 to -0.24; P < 0.01) and narrowed the A:P ratio (Estimate = -1.38; 95% CI: -2.35 to -0.41; P < 0.01). This indicates a metabolic shift toward the production of propionates, although the total concentration of volatile fatty acids (VFA) did not change significantly (Estimate = 0.27 mM, P > 0.05).

Digestibility and animal performance

Digestibility responses to forage chop length were generally low but significant for total dry matter. DMD was significantly increased (Estimate = 0.64%; 95% CI: 0.20 to 1.09; P < 0.01), signaling improved nutrient availability likely resulting from an expansion in surface area available for microbial attachment (Table 3). In contrast, fiber digestibility did not show any significant response, as neither neutral detergent fiber digestibility (NDF-D; P = 0.86) nor acid detergent fiber digestibility (ADF-D; P = 0.42) was affected. This implies that particle size reduction may be insufficient to overcome the structural barriers set by lignification and the plant cell wall, which restrict microbial access to cellulose and hemicellulose.

Animal performance metrics showed that shorter chop lengths significantly increased DMI (Estimate = 0.42 kg/d; 95% CI: 0.02 to 0.81; P < 0.05) and organic matter intake (OMI; Estimate = 0.57 kg/d; 95% CI: -0.01 to 1.15; P = 0.05). Growth indicators also improved, with a significant increase in body weight gain (Estimate = 1.85 kg; 95% CI: 1.11 to 2.58; P < 0.01) and BWG rate (Estimate = 2.88 g/d, P < 0.01), despite high heterogeneity across studies (Table 3).

Milk production responses

Milk production responses were in line with observed digestibility patterns. There was a tendency for milk yield to rise (Estimate = 0.18 kg/d; 95% CI: -0.01 to 0.36; P = 0.06), which likely reflects the increased energy availability from elevated DM digestibility (Table 3). However, this was accompanied by a significant reduction in milk fat concentration (Estimate = -0.28%; 95% CI: -0.55 to 0.00; P = 0.05). This decrease was probably due to the reduced intake of physically effective NDF and subsequent alterations in rumen fermentation. Milk protein and lactose concentrations were not significantly affected, demonstrating low sensitivity to forage particle size changes. The high level of interaction between chop length, forage quality, and diet structure suggests that these factors must be optimized as part of an integrated feeding approach.

Correlation between chop length and dry matter intake

The meta-regression analysis established a significant positive correlation between forage chop length and dry matter intake (DMI), described by the mathematical model $y=-0.043+0.029x$ (Figure 2). According to this framework, each 1 mm reduction in chop length is associated with a 0.029 kg/day increase in DMI. These findings align with the study's overall meta-analysis estimate of 0.42 kg/d. However, the substantial heterogeneity (I^2= 83.22%) indicates that responses are context-dependent; specifically, intake increases are more pronounced in forage-based diets and less consistent in high-concentrate rations.

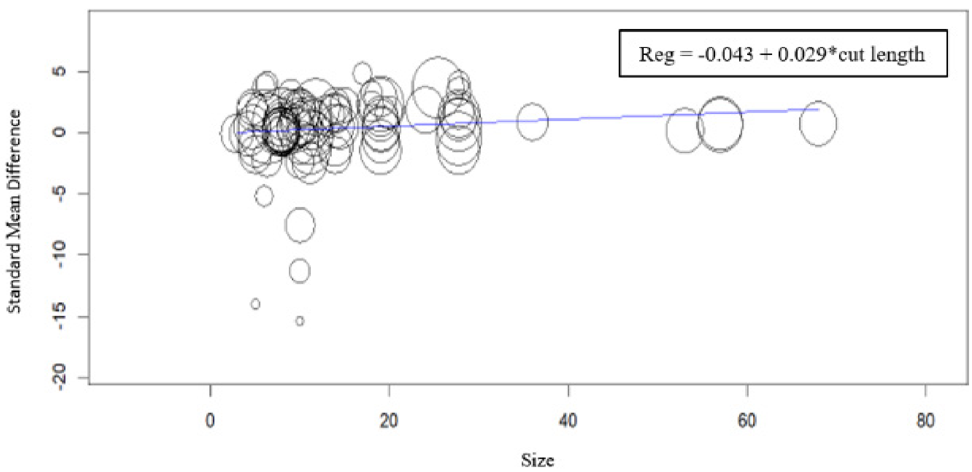

Figure 2: Meta-regression parameter of dry matter intake and chop length.

DISCUSSION

Silage quality

This meta-analysis aimed to examine the effect of forage chop length on silage quality, including DM preservation and fermentation properties. Shorter chop lengths resulted in better compaction, better oxygen exclusion, and lower DM losses, which supported better DM preservation. These effects are largely attributed to the increase in packing density, which is especially important for high-DM forages. Kung *et al.* (2018) reported lower storage losses in finely chopped, high-DM silages with adequate packing, while Sun *et al.* (2020) showed higher fermentation by reducing pH and an increase in the concentration of lactic acid when particle size was reduced to 1-2 cm.

Although these advantages existed, the fermentation in response to the shortening of chop length varied. Parameters like pH and organic acid levels often had negligible variation, indicating that forage moisture, epiphytic microflora, and inoculants have a stronger influence on the fermentation outcomes. Previous studies have confirmed that moisture control and additive application have a bigger effect on fermentation efficiency than particle size (Bhandari *et al.*, 2007; Muck *et al.*, 2018).

Chop length had a slight effect on CP, neutral detergent fiber (NDF), and acid detergent fiber (ADF), none of which were significant. This means that additives like enzymes or microbial inoculants showed more consistent effects on the quality of fermentation and protein preservation (Rinne *et al.*, 2020; Wang *et al.*, 2025) compared to physical preservation, primarily caused by the length of the chop. The presence of high heterogeneity among the studies indicates strong effects of forage species, maturity, ensiling method, and storage time (Muck *et al.*, 2018; McDonald *et al.*, 2011). In general, chop length reduction causes better DM preservation but does not necessarily guarantee improved fermentation quality, underscoring the need for combined silage management.

Rumen fermentation dynamics

Forage chop length affects rumen fermentation processes by changing the particle size, digestion rate, and chewing activity. Smoother particles expose more area to microbial invasion and tend to increase the rate of acetate to propionate conversion. This exposure promotes propionate generation and enhances energy metabolism (Sun *et al.*, 2021). However, decreased chewing and saliva secretion could reduce the buffering capacity of the rumen, potentially leading to subacute ruminal acidosis (SARA) (Yang and Beauchemin, 2009; McDonald *et al.*, 2011).

The responses of total volatile fatty acid (VFA) concentration, ruminal ammonia nitrogen (NH_3-N), and individual VFA profiles to forage chop length were inconsistent across the studies included in this meta-analysis. These findings suggest that ruminal fermentation characteristics are influenced more strongly by diet composition, forage quality, and fiber digestibility than by particle size alone (Einarson *et al.*, 2004; Bhandari *et al.*, 2008). Although some studies reported higher fermentation rates with smaller particle sizes, others detected no significant changes in ruminal pH or VFA concentrations (Couderc *et al.*, 2006; Wang *et al.*, 2020). These contrasting responses likely reflect differences in forage species, dietary composition, and experimental conditions, further highlighting the context-dependent effects of forage chop length on rumen fermentation.

Previous studies suggest that a chop length of about 10–19 mm gives an equilibrium between fermentation and rumen stability (Randby *et al.*, 2024). Conversely, excessively long particles (longer than 19 mm) could slow down the digestion process and reduce intake (Johnson *et al.*, 2003). The substantial variability of results indicates intricate interactions between the size of particles, diet organization, and microbial adjustment. Further studies need to be done regarding diet-specific interactions and long-term implications on rumen health and microbial ecology.

Digestibility

An increase in both the dry matter digestibility (DMD) and organic matter digestibility (OMD) improves nutrient availability and energy use in high-producing ruminants (McDonald *et al.*, 2011). However, the substantial heterogeneity among studies indicates that responses vary considerably, likely reflecting differences in forage species, silage quality, diet composition, animal characteristics, and experimental design. The response to forage chop length optimization is closely associated with the structural characteristics of the forage, particularly fiber concentration and the degree of lignification, which influence particle breakdown, microbial accessibility, and ultimately nutrient digestibility.

Similarities in DMD and OMD trends indicate that physical processing has the potential to increase organic degradation, but is not always consistent. Although the small size of particles increases physical accessibility, rumen microbial activities, maturity of forage, and ensiling conditions also have a strong effect on the OMD. This implies that particle size reduction is not enough to maximize digestion.

Shortening forage chop length did not significantly improve neutral detergent fiber digestibility (NDF-D) or acid detergent fiber digestibility (ADF-D). The lack of improvement is likely constrained by lignin concentration and the structural architecture of the plant cell wall, which reduce the accessibility of cellulose and hemicellulose to ruminal microorganisms and their fibrolytic enzymes, thereby limiting fiber degradation despite smaller particle sizes (Van Soest, 1994). The high variability of fiber digestibility (I^2 > 70%) shows the significance of forage maturity, lignification, and ensiling strategies. As stated in a previous study, reduced fiber digestibility responses can partially be offset by increased DMI reported with shorter chop lengths (Bhandari *et al*., 2008; Randby *et al*., 2024). Optimizing chop length has context-dependent effects and is most effective when combined with complementary strategies such as enzymes, alkali treatments, or microbial inoculants (McDonald *et al*., 2011; Zebeli *et al*., 2012).

Milk production performance

The meta-analysis study indicates that there is a complex correlation between forage chop length and milk production. The positive relationship between milk yield (P = 0.06; I^2 = 32.26%) shows that shorter chop lengths could enhance feed efficiency, but responses to these changes differed between production systems. Similarly, Randby *et al*. (2024) found greater milk yield and reduced feed energy with finely chopped silage.

The milk fat tended to decrease (P= 0.06), presumably because of lower peNDF and changes in the acetate-to-propionate ratio. The decrease in rumen buffering capacity due to finer particles could also heighten the risk of subacute ruminal acidosis (SARA; pH < 5.6), which limits acetate production and the production of milk fat (Bhandari *et al*., 2008; McDonald *et al*., 2011). Milk protein (P = 0.95) and lactose (P = 0.89; I^2 = 0.00%) were mostly not affected by this, as both depend on the amount of dietary proteins, the balance of energy, and the availability of glucose, but not on the forage particle size (Bal *et al*., 2000; Randby *et al*., 2024). These results indicate a trade-off: Shorter chop length can improve efficiency and yield, but smaller milk fat makes it clear that particle size needs to be balanced with the general composition of the diet and the health of the rumen (Wang *et al*., 2020).

Performance of feed intake and body weight gain

This meta-analysis demonstrates that forage chop length influences feed intake and growth performance in ruminants. Specifically, reducing forage chop length significantly increased dry matter intake (DMI; P = 0.04) and organic matter intake (OMI; P = 0.05), indicating greater voluntary feed intake and nutrient consumption. Increased intake may result from improved forage handling, faster ruminal passage rate, and enhanced accessibility of fermentable substrates. However, the high heterogeneity observed for DMI (I^2 = 83.22%) and OMI (I^2 = 78.95%) suggests that these responses were strongly influenced by differences in forage species, total mixed ration (TMR) composition, feed additive supplementation, and animal-related factors among the included studies (Bhandari *et al*., 2008; Couderc *et al*., 2006; Harahap *et al*., 2022).

A positive, although non-significant, effect was observed for neutral detergent fiber intake (NDFI), whereas acid detergent fiber intake (ADFI) remained unaffected by forage chop length. These findings suggest that reducing particle size alone has limited capacity to improve the utilization of highly lignified fiber fractions, as lignin and plant cell wall architecture continue to restrict microbial access to structural carbohydrates (Johnson *et al*., 2003). Consequently, although reducing forage chop length can increase voluntary feed intake, additional processing strategies may be required to enhance fiber utilization, particularly in forages with high lignin concentrations.

Body weight gain (BWG) tended to increase with shorter chop lengths; however, responses varied substantially among studies (I^2 = 96.45%), reflecting differences in forage quality, diet composition, breed, physiological status, and metabolic efficiency (Bhandari *et al*., 2007; Randby *et al*., 2024). The large Cochran's Q statistic (Q = 591.36) further confirms considerable between-study heterogeneity, indicating that the effects of forage chop length are highly context-dependent. Therefore, additional research is needed to identify the forage, dietary, and animal-related conditions under which chop length optimization can most effectively improve growth performance and feed utilization in ruminant production systems (Bhandari *et al*., 2008; McDonald *et al*., 2011).

Comparison of chop length with other silage management strategies

Chop length is only one determinant of silage quality. Other factors, including microbial inoculants and moisture management, play equally important roles in fermentation efficiency and preservation (Ridla and Uchida, 1997). Lactic acid bacteria (LAB) inoculants have been shown to improve fermentation stability by accelerating lactic acid production and reducing pH more effectively than chop length adjustment alone (Muck *et al*., 2018). It is also essential to maintain moisture content because too dry or wet forages cause variability in pH regulation and organic acid synthesis (Ridla *et al*., 2024). These results suggest that to ensure a steady gain in silage preservation and silage usage, the optimum chop length needs to be combined with the use of inoculants and moisture control.

Correlation between chop length and dry matter intake

Meta-regression analysis demonstrated a significant positive association between forage chop length and dry matter intake (DMI), as described by the linear regression model ($y=-0.043+0.029x$). This finding suggests that forage particle size is an important determinant of voluntary feed intake, although the magnitude of the response is likely influenced by forage quality, diet composition, and animal-related factors among individual studies. Each 1 mm reduction in chop length increased DMI by 0.029 kg/day, consistent with the meta-analysis estimate (Estimate = 0.42 kg/d, $P < 0.01$). However, substantial heterogeneity (I^2 = 83.22%) indicates that responses varied with forage type, diet composition, and animal characteristics. For example, Randby *et al*. (2024) reported a 2.0 kg/day increase in DMI at a chop length of 19 mm, Haselmann *et al*. (2019) observed a 1.8 kg/day increase when particle size was reduced from 52 mm to 7 mm, and Randby *et al* (2008) reported a 1.3 kg/day increase at 24 mm compared with unchopped silage. These findings suggest that the intake response to finer chopping is more pronounced in forage-based diets and less consistent in high-concentrate rations.

CONCLUSION

This meta-analysis suggests that forage chop length affects silage preservation and nutrient utilization, but needs to be controlled. Reduction in chop length tended to increase feed consumption and digestibility, but decreased peNDF, which could limit rumen buffering capacity and decrease the synthesis of milk fat. The wide variation across studies shows that no particular length of chop is the best, and adequate targets must be based on forage species, ensiling conditions, and production goals. Variability in fiber digestibility, especially NDF-D and ADF-D, also indicates that mechanical processing alone is insufficient to fully exploit fiber. These results demonstrate the necessity to combine chop length modification with some complementary measures, like enzyme use, alkali treatment, or feed formulation, to enhance overall digestibility and feed efficiency. Future studies should clarify long-term effects on microbial colonization, rumen pH stability, and nutrient partitioning to refine forage processing recommendations.

To guide practical decision-making, practitioners should adopt a contextual framework: for predominantly forage-based diets, targeting the lower end of the range (~10 mm) is advised to maximize energy availability, as every 1 mm reduction is associated with a 0.029 kg/d increase in DMI. In contrast, for high-concentrate rations, a length closer to 19 mm should be maintained to mitigate the significant reduction in milk fat concentration (-0.28%) and the risk of subacute ruminal acidosis (SARA).

The high variability in fiber digestibility ($I^2 > 70\%$) indicates that mechanical processing alone is insufficient to fully exploit fiber. Therefore, future research must address three specific questions: (1) What are the distinct optimal chop thresholds for grass versus legume forages? (2) How do specific microbial inoculants interact with particle size to enhance the stability of high-moisture silages? and (3) What are the long-term effects of varying chop lengths on ruminal microbial colonization and nutrient partitioning? Addressing these will refine integrated forage processing strategies for sustainable ruminant production.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support provided by the Department of Nutrition and Feed Technology, Faculty of Animal Science, IPB University, and the Center for Tropical Animal Studies (CENTRAS), IPB University, for providing research facilities and academic support during the study. The authors also sincerely thank all individuals involved in the literature search, data compilation, statistical analysis, and manuscript preparation. Their valuable contributions were essential to the completion of this meta-analysis.

NOVELTY STATEMENT

This study represents the first multi-species meta-analysis to quantitatively integrate the entire forage processing chain, from preservation characteristics to rumen fermentation and productivity, across dairy, beef, and small ruminant systems. While previous research often focused on specific sectors like dairy cattle, this study fills a critical gap by providing a unified quantitative framework to resolve inconsistencies across 61 independent trials. It introduces the first predictive meta-regression model to quantify dry matter intake responses based on precise particle size reductions, offering an evidence-based tool for optimizing the efficiency and sustainability of diverse ruminant production systems.

AUTHOR'S CONTRIBUTION

Conceptualization was carried out by MR. Data curation, methodology, investigation and writing (original draft) by HRA, STR, and MR. Formal analysis by HRA, MSD, and RIK. Software by HRA, DRA, MSD, and RIK. Validation by HRA, STR, MSD, RIK, and MR. Writing (review and editing) by HRA, DRA, and MR.

Ethics approval

Not required, as this study is a meta-analysis of previously published data.

Generative AI and AI assisted technology statement

The authors declare that no generative AI or AI-assisted technologies were used in the creation of this manuscript.

Conflict of interest

We certify that there is no conflict of interest with any financial, personal, or other relationships with other people or organizations related to the material discussed in the manuscript.

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