Optimizing Cichorium intybus var. Chico cutting age for biomass production, greenhouse gas emissions flux, and improved performance of thin-tailed sheep

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Article

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Abstract

Forage harvest management shapes productivity and the environmental cost of ruminant systems, yet emissions from growing the forage are seldom measured alongside its feeding value. This study examined how the cutting age of *Cichorium intybus* var. Chico (*Cichorium intybus* var. Chico) governs biomass yield, greenhouse gas (GHG) emissions, and downstream performance of thin-tailed sheep. A field experiment compared two cutting ages (40 and 60 days after regrowth) for biomass and in situ CO_2, CH_4, and N_2O fluxes measured by a static closed chamber. A separate feeding trial offered 20 thin-tailed sheep four diets in which *C. intybus* var. Chico replaced concentrate at 15, 25, 35, and 45% of dry matter (G1 to G4), recording intake, nutrient digestibility, and growth. Cutting at 40 days nearly doubled CO_2 flux (164.22 vs 84.52 mg/m²/day; $P < 0.01$), whereas N_2O and CH_4 fluxes, fresh biomass (4.39 vs 4.91 ton/ha), and all yield-scaled emission intensities did not differ between ages. In sheep, higher *C. intybus* var. Chico inclusion kept dry matter intake stable while increasing crude protein intake ($P < 0.001$). Dry matter digestibility, organic matter, crude fiber, and crude protein increase with *C. intybus* var. Chico level, peaking at 35–45% inclusion. Average daily gain increased from 94.57 g (G1) to 129.76 g (G4), and feed conversion ratio improved from 6.37 to 4.58 ($P < 0.001$). Harvesting at 40 days delivers comparable biomass and emission intensity, and *C. intybus* var. Chico can replace up to 45% of concentrate while improving sheep performance, supporting sustainable tropical sheep production.

1 Introduction

Livestock production accounts for about 14.5% of global anthropogenic greenhouse gas (GHG) emissions and remains central to debates on sustainable agricultural development (Gerber et al. 2013). Most mitigation research has concentrated on enteric methane and manure management, whereas emissions from the forage production base that sustains ruminant systems have received far less attention. The omission matters because forage cultivation drives carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) fluxes from agricultural soils. Of these gases, N_2O is the one of greatest concern: its 100-year global warming potential is roughly 273 times that of CO_2, and its long atmospheric lifetime compounds the warming effect (IPCC 2021). Because soil GHG fluxes track plant growth, nutrient uptake, and rhizosphere activity, agronomic decisions that change plant physiology also change the environmental footprint of the forage stand (Vives-Peris et al. 2019).

Harvest management is among the agronomic levers with the strongest influence on both productivity and environmental performance. Cutting age fixes the developmental stage at harvest and, with it, biomass accumulation, the partitioning of carbon between shoots and roots, the quantity and composition of root exudates, and nitrogen use efficiency (Vives-Peris et al. 2019). Younger stands tend to be metabolically active and to release more labile carbon into the rhizosphere, which can prime the microbial nitrification and denitrification pathways that generate N_2O, whereas older stands divert resources toward structural tissue and conserve nutrients (Yin et al. 2023). Management events that disturb the sward and alter substrate supply can substantially shift soil N2O fluxes (Li et al. 2026). An optimal cutting age therefore has to reconcile forage yield against soil emissions, yet for most forage crops, the emission side of that trade-off is barely documented.

Cichorium intybus (*C. intybus*) combines nutritional quality with a bioactive profile, making it attractive for sustainable ruminant production. *C. intybus* accumulates crude protein, inulin, flavonoids, condensed tannins, and sesquiterpene lactones, and these compounds have been linked to better nutrient utilization, improved rumen function, higher digestibility, and lower enteric methane output (Khorshid et al. 2015; Nwafor et al. 2017; Niderkorn et al. 2019; Rodriguez et al. 2020; Ford et al. 2024). The methane response is mechanistically plausible: condensed tannins and related plant secondary metabolites modify rumen fermentation and suppress methanogen activity, with the most consistent effects reported in tropical feeding systems (Aboagye and Beauchemin 2019; Ku-Vera et al. 2020). Feeding trials have repeatedly shown gains in intake, digestibility, feed efficiency, and animal performance (Sun et al. 2012; Niderkorn et al. 2019; Rodriguez et al. 2020). Almost all of this work stops at the animal. The environmental cost of growing C. intybus and how that cost changes with harvest age remains essentially unexamined.

The question carries particular weight in tropical small-ruminant systems such as those in Indonesia, where thin-tailed sheep underpin rural livelihoods and household food security but often underperform because forage quality fluctuates and concentrate is expensive (Gunawan et al. 2026). A functional forage that supplies on-farm protein could ease both constraints simultaneously, boosting nutrient supply while reducing reliance on purchased inputs, in *C. intybus* var. Chico, specifically, delaying harvest increases biomass but reduces digestibility (Zaini et al. 2021), the same yield-quality trade-off that motivates this study. What remains unresolved is how cutting age jointly governs biomass yield, GHG emissions, and the feeding value of *C. intybus* var. Chico for animal, where these plants' agronomic characteristics are only beginning to be characterized.

This study examined two cutting ages of *Cichorium intybus var. Chico*, 40 and 60 days after regrowth, and traced their effects across the production chain: biomass yield, soil emissions of CO_2, CH_4, and N_2O, and the feed intake, nutrient digestibility, and growth of thin-tailed sheep offered *C. intybus* var. Chico-based diets. We hypothesized that cutting age would alter plant productivity and GHG emissions, and that these agronomic shifts would propagate into the nutritional value of the forage and the performance of the animals consuming it. Measuring agronomic, environmental, and animal responses within a single system provides a more complete account of how harvest timing shapes the productivity and sustainability of sheep production than any single response could.

2 Methodology

2.1 Study sites and soil profiling conditions

The study was conducted at two sites in the Special Region of Yogyakarta, Indonesia, which has a tropical climate. The field experiment on biomass and soil GHG fluxes was established at the Research

Field of the Faculty of Animal Science, Universitas Gadjah Mada (UGM) (7°46' S, 110°22' E; 114 m a.s.l.) on a regosol. Air temperature, relative humidity, and rainfall during the experiment were obtained from the Meteorology, Climatology, and Geophysics Agency station in Sleman, Yogyakarta (Fig. 1). Gas samples were analyzed at the Laboratory of Agricultural Environment, BPSI-Yogyakarta. The feeding trial was conducted at Suket Ijo Farm, Wedomartani, Sleman. Before planting, the soil was sampled and characterized, with a pH of 7.16 (neutral), water content of 26.35%, organic matter of 7.25%, and total nitrogen of 0.19% (Table 1)

Table 1
Soil physicochemical properties at the experimental site.

Parameter	**Value**	**Category**
Water content (%)	26.35	Moderate
pH (H_2O)	7.16	Neutral
Organic matter (%)	7.25	High
Total nitrogen (%)	0.19	Moderate

2.2 Experimental design

The study comprised two linked components: a field experiment that quantified the agronomic and environmental response of the forage to cutting age, and an *in vivo* feeding experiment that tested the nutritional consequences of the harvested forage for sheep.

In the field component, biomass production and soil greenhouse gas (GHG) emissions were evaluated for two cutting ages of *Cichorium intybus var. Chico*, 40 and 60 days after regrowth. These two ages bracket the window in which *C. intybus* var. Chico shifts from active vegetative growth toward stem elongation, the stage at which the yield-quality trade-off becomes most pronounced (Zaini et al. 2021). Each cutting age was assigned to five plots in a completely randomized block design, yielding 10 experimental plots in total. Individual plots measured 100 × 100 cm and were separated by 80 cm buffers to limit edge effects and cross-plot interference during canopy gas sampling. Within each plot, biomass yield and the proximate composition of the harvested forage were determined, while soil GHG fluxes (CO_2, CH_4, and N_2O) were measured in situ by the static closed-chamber method. Because the comparison involved a single factor at two levels, treatment means for each response variable were compared using an independent-samples t-test.

The *in vivo* trial followed a completely randomized design with four dietary treatments and five replicate animals per treatment, giving 20 thin-tailed sheep in total. The treatments differed in the proportion of concentrate replaced by *C. intybus* var. Chico on a dry matter (DM) basis: G1 (50% concentrate + 15% *C. intybus var. Chico*), G2 (40% concentrate + 25% *C. intybus var. Chico*), G3 (30% concentrate + 35% *C. intybus var. Chico*), and G4 (20% concentrate + 45% *C. intybus var. Chico*). Across all treatments, *P. purpureum cv.* Gama Umami was held constant at 35% of the ration, so that the concentrate to *C. intybus* var. Chico substitution was the only dietary variable (Tables 2 and 4). The diets were formulated to be comparable in crude protein (16.0 to 17.0% DM) and total digestible nutrients (64.0 to 65.7% DM), which isolated the effect of the *C. intybus* var. Chico inclusion gradient on feed intake, nutrient digestibility, and growth performance.

2.3 Greenhouse gas emission measurement

Greenhouse gas fluxes were quantified using the static closed-chamber method. A chamber (20 × 30 × 35 cm) was fitted over the standing canopy and sealed against a pre-installed base to prevent leakage. Each chamber carried a thermometer to log headspace temperature, and the internal air was mixed immediately before each draw. Headspace gas was sampled with a syringe at 0, 10, 20, and 30 min after closure, in two daily sessions, morning (06:00–09:00) and midday (12:00–14:00), and stored in sealed vials for transport to the laboratory. Concentrations of CO_2 (ppm), CH_4 (ppm), and N_2O (ppb) were determined by gas chromatography calibrated against certified standard gases. A flux was retained only when the four-point change in concentration was approximately linear over the 30 min closure, and was calculated as:

$$F = (\Delta C/\Delta t) \times (V/A) \times (M/Vm) \times 273/(273 + T)$$

where F is the gas flux (mg m^{-2} day^{-1}), $\Delta C/\Delta t$ is the slope of headspace concentration over time, V is the chamber volume, A is the basal area enclosed, M is the molar mass of the gas, Vm is the molar volume at standard temperature and pressure, and T is the headspace temperature (°C). The two-session fluxes were averaged to a daily flux for each plot.

2.4 Biomass production

At each target cutting age (40 or 60 days after regrowth), all above-ground biomass within the plot was cut at 5 cm above ground level and weighed immediately to record fresh weight according to methods described by Putra et al. (2026). A representative sub-sample was weighed fresh, oven-dried at 55°C to a constant weight to determine DM content, and then ground to pass a 1 mm screen for chemical analysis. Proximate composition was determined following AOAC (2005): ash by furnace combustion with OM obtained by difference, CP by the Kjeldahl method (N × 6.25), CF by sequential acid-base digestion, and ether extract (EE) by Soxhlet extraction. Fresh biomass per plot was scaled to fresh yield per hectare (ton/ha) from the harvested plot area, and DM yield was derived from the corresponding DM content.

2.5 Animals, housing, and diets

Twenty male thin-tailed sheep, with an average weight of 15 ± 2.5 kg (mean ± SD), were selected for the feeding trial. These sheep were obtained from a commercial sheep farm in Yogyakarta, Indonesia, and were approximately 10 months old. Each animal was housed individually (70 × 150 × 100 cm; L × W × H) fitted with separate trays for total collection of feces and urine, and with clean drinking water available at all times. Before the trial, all sheep were drenched with Leva-200® (levamisole; 1 mL per 20 kg body weight) to clear gastrointestinal nematodes and were shorn to obtain an accurate net body weight and to reduce the risk of heat stress during confinement. Animals were ear-tagged for identification and inspected daily for signs of ill health throughout the study.

Diets were formulated on a DM basis to be comparable in CP and TDN across treatments, with *P. purpureum cv.* Gama Umami was fixed at 35% of the ration in all groups. The remaining 65% comprised concentrate and *C. intybus* var. Chico in the proportions that defined G1 to G4, so that *C. intybus* var. Chico progressively replaced concentrate as the dietary protein source (Tables 2 and 3). The commercial concentrate (JF49®) consisted of wheat bran, copra meal, cassava pulp, corn bran, corn gluten feed, and dried distillers' grains with solubles. *P. purpureum cv. Gama Umami* and *C. intybus* var. Chico was harvested from the forage fields of the Faculty of Animal Science, UGM, and the grass was chopped to 4–6 cm in length before feeding. The total ration was offered at 3.5% of a DM basis requirement in two equal meals at 08:00 and 16:00; concentrate and *C. intybus* var. Chico was mixed and offered first, followed by the grass at the set ratio. Clean drinking water was available at all times.

Table 2
Nutrient content (%) of feed ingredients

Nutrients content	***P. purpureum* cv. Gama Umami**	***C. intybus* var. Chico**	**JF49® concentrate**
Dry matter	20.55	9.89	90.60
Organic matter	85.54	89.17	92.06
Ash	14.46	10.83	7.94
Crude fiber	32.50	10.70	10.97
Extract ether	1.33	2.85	6.94
Crude protein	10.76	21.36	18.13
Nitrogen-free extract	40.95	44.37	56.02
Total digestible nutrient	53.75	67.85	73.39

Table 3
The proportion of feed ingredients and nutrient content (%) of ration treatment

Materials	Group Treatment			
	G1	**G2**	**G3**	**G4**
P. purpureum cv. Gama Umami	35	35	35	35
C. intybus var. Chico	15	25	35	45
JF49® concentrate	50	40	30	20
Nutrient content				
Dry matter	53.98	45.91	37.83	29.76
Crude fiber	18.47	18.44	18.41	18.38
Extract ether	4.36	3.95	3.54	3.14
Crude protein	16.04	16.36	16.68	17.01
Nitrogen-free extract	49.00	47.83	46.67	45.50
Total digestible nutrient	65.69	65.13	64.58	64.02

2.6 In vivo trial procedures

The feeding trial comprised a 14-day adaptation period followed by a six-week data-collection period. During adaptation, sheep were accustomed to the pen and their assigned diets, with water available at all times, under the same feeding schedule (08:00 and 16:00). Initial body weight was recorded at the end of adaptation. Animals were weighed every two weeks thereafter, before the morning feeding, to track growth while limiting handling stress. All experimental procedures involved routine animal handling and non-invasive measurements. Consequently, neither anesthesia nor euthanasia was necessary or administered during the study. Daily feed intake was calculated for each animal as the difference between the DM offered and the DM refused. Over the final 10 days, a total collection of feces was performed, with feces removed and weighed each morning before feeding; feed, refusal, and fecal samples were sub-sampled, stored at – 20°C, then pooled per animal and analyzed proximately following the AOAC (2005) methods. Apparent nutrient digestibility was calculated as the fraction of each ingested nutrient not recovered in the feces. Average daily gain (ADG) was obtained from the change in body weight over the trial, and the feed conversion ratio (FCR) was calculated as DM intake divided by body weight gain.

2.7 Statistical analysis

Biomass and GHG data from the field component (two cutting ages) were analyzed as a single-factor comparison and tested by an independent-samples t-test. Data from the *in vivo* trial were analyzed using one-way analysis of variance (ANOVA) for the completely randomized design (CRD), with diet as the fixed effect and the individual animal as the experimental unit. When the F-test was significant, treatment means were separated by Duncan's Multiple Range Test (DMRT). Normality and homogeneity of variance were checked before analysis using Shapiro-Wilk and Levene tests. All analyses were performed in IBM SPSS Statistics version 30, with statistical significance declared at $P < 0.05$.

3 Results and discussion

3.1 Greenhouse gas accumulation dynamics

The findings of the present study demonstrate that cutting timing significantly affected CO_2 flux but had no significant effect on N_2O or CH_4 flux (Table 4). *C. intybus* var. Chico harvested at 40 days exhibited a CO_2 flux of 164.22 mg/m²/day, which was nearly twice the 84.52 mg/m²/day recorded at 60 days ($P < 0.01$). This difference is closely associated with the physiological stage of plant development. At 40 days, *C. intybus* var. Chico remained in the active vegetative phase, characterized by rapid biomass accumulation and a substantial supply of labile carbon to the rhizosphere. These conditions stimulate root respiration, leading to greater CO_2 emissions. By 60 days, however, plant growth had slowed, and structural tissues comprised a larger proportion of the biomass, reducing carbon allocation and, consequently, decreasing CO_2 efflux. Similar patterns have been reported in sorghum, where CO_2 emissions peak during the vegetative stage before declining during ripening (Kuang et al. 2021). The greater CO_2 efflux observed in 40-day-harvested *C. intybus* var. Chico can be attributed to several physiological and rhizosphere processes. As a C_3 species, *C. intybus* var. Chico exhibits relatively high photorespiration rates, accounting for approximately 30–40% of gross photosynthesis. In addition, its inulin-rich taproot releases readily fermentable fructooligosaccharides into the rhizosphere, which can stimulate microbial decomposition through a priming effect and the rosette growth habit of *C. intybus* var. Chico also promotes a moist soil-surface microclimate, further enhancing microbial activity and soil respiration.

In contrast to CO_2, cutting age did not significantly affect N_2O flux (3.51 vs. 4.20 mg/m²/day). N_2O emissions are primarily regulated by nitrification and denitrification processes, which depend on mineral nitrogen availability, soil moisture, and soil aeration rather than on the timing of defoliation itself (Malyan et al. 2025; Hassan et al. 2022a). Moreover, the influence of plants on N_2O emissions is not unidirectional. Root activity may either suppress or enhance N_2O production depending on the balance between the supply of labile carbon that stimulates denitrification and the inhibition of nitrification within the rhizosphere (Xie et al. 2023). Consequently, within the cutting interval evaluated in the present study, N_2O dynamics appear to have been governed more by prevailing soil conditions than by differences in harvest timing.

Similarly, CH_4 flux did not differ significantly between cutting ages (0.03 vs. 0.02 mg/m²/ day). The consistently low CH_4 flux indicates that the experimental system remained nearly methane-neutral, a characteristic commonly observed in well-aerated upland soils where methane oxidation by methanotrophic bacteria exceeds methane production. Le Mer and Roger (2001) reported that CH_4

oxidation rates in upland soils rarely exceed 0.1 mg/m²/h, while large-scale field surveys have shown that agricultural soils generally function as either very weak CH_4 sources or near-neutral systems, with methane exchange being controlled primarily by soil moisture and aeration status (Cowan et al. 2020). Given that the observed CH_4 fluxes were extremely small and close to the analytical detection threshold, it is reasonable to conclude that differences in cutting age did not produce measurable changes in methane exchange.

Table 4
Greenhouse gas flux and emission intensity per unit fresh biomass production of *C. intybus* var. Chico at different cutting ages

Variables	**Cutting age**		**Sig.**
	40-days	**60-days**	
GHG flux			
CO_2 (mg/m²/day)	164.22 ± 35.61	84.52 ± 14.31	**
N_2O (mg/m²/day)	3.51 ± 1.17	4.20 ± 2.59	ns
CH_4 (mg/m²/day)	0.03 ± 0.01	0.02 ± 0.01	ns
GHG emission intensity			
CO_2 (mg/kg/day)	26.74 ± 6.30	22.92 ± 3.10	ns
N_2O (mg/kg/day)	1.85 ± 1.11	1.51 ± 0.21	ns
CH_4 (mg/kg/day)	0.02 ± 0.01	0.003 ± 0.002	ns

** = significance at $P < 0.01$, ns = no significance ($P > 0.05$). Values are presented as mean ± SD.

When emissions were expressed per unit of fresh biomass, no significant differences were observed among the three GHGs. Although CO_2 efflux was significantly greater in plants harvested at 40 days, this increase coincided with a period of rapid biomass accumulation. By contrast, plants harvested at 60 days produced greater fresh biomass despite exhibiting lower CO_2 efflux. Previous studies have consistently reported that *C. intybus* var. Chico fresh biomass increases with harvest age, both in intercropping systems in Indonesia (Zaini et al. 2021) and across a range of harvest intervals (Paucar et al. 2026; Ma et al. 2026). As a result, the carbon cost per unit of harvested biomass remained comparable between harvest ages.

Likewise, yield-scaled N_2O (1.85 vs. 1.51 mg/kg/day) and CH_4 (0.02 vs. 0.003 mg/kg/day) emission intensities did not differ significantly. Although CH_4 intensity appeared to decline by nearly an order of magnitude at the later harvest, the absolute fluxes were extremely small and highly variable, rendering the observed reduction statistically indistinguishable from measurement noise. This finding is consistent with the concept of yield-scaled greenhouse gas emissions, whereby apparent differences in area-based emissions may disappear when emissions are normalized to agricultural productivity (Xie et al. 2023). Overall, harvest age substantially influenced area-based CO_2 efflux but did not alter the greenhouse gas footprint per unit of fresh biomass. These findings suggest that harvest timing should not be determined solely based on GHG emissions. Instead, decisions should also consider the trade-off between biomass production and forage quality, as chicory generally exhibits declining crude protein concentration and digestibility with increasing harvest age (Ma et al. 2026; Paucar et al. 2026).

3.2 Biomass production

Biomass production between the two harvest ages did not differ significantly. Fresh biomass averaged 4.39 ton/ha at 40 days and 4.91 ton/ha at 60 days, representing only a ~ 12% numerical increase despite an additional 20 days of growth. This finding suggests that, within the evaluated harvest interval, biomass accumulation approached a plateau rather than continued rapid linear growth. A similar pattern was observed for dry matter yield, which increased from 0.42 to 0.48 ton/ha (~ 14%), although the difference was likewise not statistically significant. Interestingly, dry matter production remained nearly constant, accounting for ~ 9.6% and ~ 9.8% of fresh biomass at 40 and 60 days, respectively. These results indicate that delaying harvest by 20 days did not substantially increase dry matter accumulation, and the plants remained high-moisture forage regardless of harvest age.

From an agronomic perspective, the absence of significant differences in biomass production has important practical implications. Because the yield obtained at 40 days was statistically comparable to that at 60 days, a shorter cutting interval can be adopted without compromising productivity per harvest. This advantage becomes even more relevant when forage quality is considered. In many forage species, extending the defoliation interval reduces crude protein concentration and digestibility because of increasing stem development and structural tissue accumulation (Calzada-Marín et al. 2014). Conversely, shorter harvest intervals have been shown to improve both dry matter and organic matter digestibility (Patiga et al. 2020). Therefore, harvesting *C. intybus* var. Chico at 40 days may yield comparable biomass while maintaining superior nutritional quality. Furthermore, shorter harvest intervals allow more cutting cycles within a growing season, potentially increasing cumulative annual forage production even when yield per individual harvest remains unchanged.

The comparable biomass production observed at both harvest ages also helps explain the greenhouse gas emission patterns presented in Table 4. Because fresh biomass did not differ significantly, the similar CO_2 emission intensity per unit of biomass was not driven by differences in productivity but rather by the combination of comparable yields and the variability associated with CO_2 flux measurements. Consequently, although area-based CO_2 emissions were significantly greater at 40 days, the greenhouse gas footprint per unit of harvested biomass remained statistically equivalent between harvest ages. Together, these findings indicate that harvest age should be selected primarily based on forage quality and harvest frequency rather than differences in biomass yield or yield-scaled greenhouse gas emissions.

Table 5
Biomass production (ton/ha) of *C. intybus* var. Chico at different cutting ages

Variables	Cutting age		Sig.
	40-days	60-days	
Fresh biomass	4.39 ± 0.65	4.91 ± 0.80	ns
Dry matter	0.42 ± 0.09	0.48 ± 0.04	ns
Organic matter	0.33 ± 0.48	0.36 ± 0.64	ns

ns = no significance (P > 0.05). Values are presented as mean ± SD.

3.3 Effect of *C. intybus* var. Chico proportion of nutrient intake

The present study evaluated the effects of dietary combinations of *C. intybus* var. Chico and concentrate on nutrient intake, growth performance, and digestibility in thin-tailed sheep. The *C. intybus* var. Chico used in the feeding trial was the same material evaluated in the greenhouse gas emission experiment. The results showed that dietary treatments significantly affected nutrient intake (P < 0.05; Table 6), indicating that different *C. intybus* var. Chico–concentrate combinations influenced feed consumption patterns.

Dry matter intake (DMI) was highest in G1 (602.28 g/h/d), exceeding that of G2 (584.77 g; P < 0.05), although it did not differ significantly from G3 (599.61 g/h/d). Sheep that received G4 showed an intermediate DMI (593.95 g). In contrast, OMI was greatest in G3 (569.76 g), followed by G2 (556.48 g) and G4 (548.58 g), whereas G1 recorded the lowest OMI (539.99 g/h/d; P < 0.01). A similar trend was observed for CFI, with G3 (113.86 g/h/d) and G2 (112.25 g) exhibiting higher intakes than G1 (111.82 g) and G4 (110.60 g) (P < 0.001). Ether extract intake was significantly greater in G1 than in the other dietary treatments. For CPI, G4 recorded the highest value (90.12 g/h/d), although it did not differ significantly from G3 (88.69 g). Conversely, G1 had the lowest CPI (85.68 g/h/d), which was not statistically different from G2 (87.15 g/h/d).

Table 6
Feed intake of thin-tailed sheep fed with different ration treatments

Feed Intake (g/h/d)	**Group treatment**				**Sig.**
	G1	**G2**	**G3**	**G4**	
Dry matter intake (DMI)	602.28 ± 0.85^{a}	584.77 ± 14.65^{b}	599.61 ± 5.35^{a}	593.95 ± 8.59^{ab}	*
Organic matter intake (OMI)	539.99 ± 4.06^{c}	556.48 ± 6.16^{ab}	569.76 ± 13.95^{a}	548.58 ± 12.84^{bc}	**
Crude fiber intake (CFI)	111.82 ± 1.30^{c}	112.25 ± 1.63^{ab}	113.86 ± 1.87^{a}	110.60 ± 0.41^{c}	***
Extract ether intake (EEI)	29.73 ± 0.12^{a}	28.67 ± 0.43^{b}	28.72 ± 0.19^{b}	28.53 ± 0.58^{b}	*
Crude protein intake (CPI)	85.68 ± 1.05^{c}	87.15 ± 1.69^{bc}	88.69 ± 1.45^{ab}	90.12 ± 0.18^{a}	***

Asterisks indicate the significance level of *C. intybus* var. Chico inclusion as determined by ANOVA (* = significance at $P < 0.05$, ** = significance at $P < 0.01$, *** = significance at $P < 0.001$). Values are presented as mean ± SD.

Increasing the proportion of *C. intybus* var. Chico from 15% (G1) to 45% (G4), while proportionally reducing concentrate, significantly affected nutrient intake but produced only minor differences in DMI. Feed intake is a key determinant of nutrient availability for animal growth and productivity (Merwe and Brand 2020), and high dietary fiber can limit intake by increasing rumen fill and slowing digesta passage (Niderkorn et al. 2018; Valença et al. 2021). Despite the reduced concentrate inclusion, DMI remained relatively stable, indicating that *C. intybus* var. Chico effectively maintained feed acceptability and did not impair rumen function.

The favorable intake response can be attributed to the nutritional characteristics of *C. intybus* var. Chico. As a deep-rooted and drought-tolerant forage, rich in minerals and fermentable carbohydrates that enhance nutrient utilization and gastrointestinal health (Abrams et al. 2005; Vogt et al. 2015; Dicksved et al. 2015; Ivarsson et al. 2011, 2012; Putra et al. 2026). In the present study, diets containing 35% (G3) and 45% (G4) *C. intybus* var. Chico increased organic matter, crude fiber, and crude protein intake, whereas the 25% inclusion level (G2) also improved intake of organic matter, crude fiber, and ether extract. The comparable crude fiber content of *C. intybus* var. Chico (10.70%) and concentrate (10.97%), together with the slightly higher dietary crude protein in G4, likely supported rumen microbial activity, nutrient digestibility, and voluntary feed intake (Hassan et al. 2023b; Saro et al. 2023; de Oliveira et al. 2020; Knowles et al. 2017)

These findings demonstrate that *C. intybus* var. Chico can successfully replace a substantial proportion of concentrate without compromising nutrient intake, offering a practical and economically attractive feeding strategy. Similar benefits of *C. intybus* var. Chico supplementation, including improved digestibility, gastrointestinal health, and animal performance, has been reported in sheep, pigs, calves, deer, and rabbits (Ivarsson et al. 2011; Jan et al. 2011; Niderkorn et al. 2019; Nwafor et al. 2017). Given that fiber content remained similar among diets, the maintenance of nutrient intake was most likely associated with the improved nutritional quality of *C. intybus* var. Chico rather than differences in fiber content, highlighting its potential as a sustainable alternative to commercial concentrates in ruminant production systems.

3.4 Effect on nutrient digestibility

Our result demonstrated that dietary treatment significantly affected nutrient digestibility in thin-tailed sheep ($P < 0.05$; Table 7). Dry matter digestibility (DMD) was significantly greater in G3 (69.57%) and G4 (69.56%) than in G1 (67.11%) and G2 (66.54%). A comparable trend was observed for crude protein digestibility (CPD), with G3 (74.01%) and G4 (73.93%) exhibiting significantly higher values than G1 (72.45%) and G2 (72.58%). Organic matter digestibility (OMD) and crude fiber digestibility (CFD) also increased progressively with increasing *C. intybus* var. Chico inclusion. OMD improved from 72.17% in G1 to 76.01% in G4, while CFD increased from 47.28% to 53.89%. Both parameters were significantly higher in the c *C. intybus* var. Chico -containing diets than in the control treatment ($P < 0.001$), indicating that increasing dietary *C. intybus* var. Chico enhanced the digestibility of organic matter and fiber. In contrast, ether extract digestibility showed the opposite response. G1 (77.32%) and G2 (77.40%) exhibited significantly greater fat digestibility than G3 (73.38%) and G4 (72.95%) ($P < 0.001$), suggesting that higher levels of *C. intybus* var. Chico inclusion reduced ether extract digestibility despite improving the utilization of other dietary components.

The present results demonstrate that replacing commercial concentrate with *Chicory intybus* var. *Chico* significantly improved nutrient digestibility in thin-tailed sheep. Inclusion levels of 25% and, more consistently, 35–45% significantly increased the digestibility of dry matter, organic matter, and crude fiber, while crude protein and ether extract digestibility were significantly affected at the higher inclusion levels (35–45%). These responses are likely associated with the functional properties of c *C. intybus* var. Chico, which contains bioactive compounds such as esculin, coumarins, and flavonoids, has been reported to enhance intestinal structure, nutrient absorption, and digestive efficiency (Loo 2007; Merwe and Brand 2020). Increasing dietary *C. intybus* var. Chico may therefore have enhanced rumen fermentation and nutrient utilization by improving both gastrointestinal function and microbial activity.

Table 7
Nutrient digestibility coefficient of thin-tailed sheep fed with different ration treatments

Nutrient digestibility (%)	Group Treatment				Sig.
	G1	G2	G3	G4	
Dry matter	67.11 ± 0.98^{b}	66.54 ± 0.97^{b}	69.57 ± 0.20^{a}	69.56 ± 0.37^{a}	***
Organic matter	72.17 ± 0.44^{d}	73.11 ± 0.39^{c}	75.46 ± 0.30^{b}	76.01 ± 0.24^{a}	***
Crude fiber	47.28 ± 0.41^{d}	48.98 ± 0.64^{c}	52.86 ± 0.26^{b}	53.89 ± 0.39^{a}	***
Extract ether	77.32 ± 0.48^{b}	77.40 ± 0.79^{b}	73.38 ± 0.61^{a}	72.95 ± 0.65^{a}	***
Crude protein	72.45 ± 0.74^{b}	72.58 ± 1.19^{b}	74.01 ± 0.53^{a}	73.93 ± 0.46^{a}	***

Asterisks indicate the significance level of *C. intybus* var. Chico inclusion as determined by ANOVA (*** = significance at $P < 0.001$). Values are presented as mean ± SD.

Efficient rumen fermentation is essential for reducing feed particle size (Xu et al. 2025; Zhang et al. 2025), accelerating digesta passage, and optimizing nutrient digestion (Li et al. 2019). Maintaining a stable rumen microbial ecosystem is equally important because it supports consistent fermentation, efficient nutrient degradation, and energy production (de Oliveira et al. 2020; Hidayat et al. 2019), whereas abrupt dietary changes can disrupt microbial populations and impair digestive performance (Franzolin and Dehority 2010). The gradual replacement of concentrate with *C. intybus* var. Chico, in this study, appeared to maintain rumen stability while improving digestive efficiency.

The improvements in organic matter, crude fiber, and crude protein digestibility are also consistent with the dietary composition of the experimental rations. The G4 diet contained the lowest crude fiber concentration (18.38%), which likely contributed to its superior organic matter digestibility, as excessive structural fiber is known to reduce nutrient utilization. Balancing high-fiber forages with concentrates or low-fiber feed ingredients has previously been shown to enhance digestibility. In addition, the higher digestibility of crude fiber and crude protein was observed with increasing *C. intybus* var. Chico inclusion may reflect enhanced activity of the cellulolytic and proteolytic rumen microbiome, whose synergistic interactions are fundamental to efficient degradation of plant cell walls and dietary protein (Ferreira et al. 2013).

3.5 Effect on sheep performance

As demonstrated in Table 8, dietary treatment had a significant impact on the growth performance of thin-tailed sheep, as evidenced by variations in ADG and FCR ($P < 0.05$). The ADG increased progressively from 94.57 g at G1 to 129.76 g at G4 treatment, although the value for G4 did not differ significantly from that of G3 (125.11 g). The results of the study indicate that improved diet quality is associated with greater body weight gain. A comparable trend was observed for FCR, which decreased from 6.37 in G1 to 4.58 in G4, indicating enhanced feed utilization alongside improved dietary quality. The presence of significant differences among treatments ($P < 0.001$) confirms that the dietary interventions enhanced feed efficiency. Overall, G4 showed the greatest growth performance, achieving the highest ADG and the lowest FCR. However, its ADG was not statistically different from that of the G3 group, suggesting that both dietary treatments effectively improved sheep productivity.

Table 8
Thin-tailed sheep performance fed with different ration treatments

Performance	**Group Treatment**				**Sig.**
	G1	**G2**	**G3**	**G4**	
ADG (g/head/day)	94.57 ± 2.32^{c}	104.47 ± 5.85^{b}	125.11 ± 2.94^{a}	129.76 ± 4.44^{a}	***
FCR	6.37 ± 0.14^{a}	5.60 ± 0.31^{b}	4.79 ± 0.14^{c}	4.58 ± 0.17^{c}	***

Asterisks indicate the significance level of *C. intybus* var. Chico inclusion as determined by ANOVA (*** = significance at $P < 0.001$). Values are presented as mean ± SD.

Growth performance in the present study was evaluated using average daily gain (ADG) and feed conversion ratio (FCR). Both parameters were significantly affected by dietary treatment ($P < 0.05$), indicating that replacing concentrate with *C. intybus* var. Chico improved animal performance. In ruminants, ADG is primarily determined by nutrient intake, nutrient digestibility, and the efficiency with which absorbed nutrients are converted into body tissue (Shiningavamwe et al. 2025). This relationship was evident in the present study, where treatments with the greatest nutrient digestibility also achieved the highest ADG and the most efficient FCR.

Previous studies have likewise demonstrated that differences in feed digestibility substantially influence sheep growth performance and feed efficiency (Hao et al. 2020; Shiningavamwe et al. 2025). The highest ADG and the lowest FCR were obtained in G4, in which 45% of the concentrate was replaced with *Chicory intybus* var. *Chico*. These improvements are likely attributable to the higher diet digestibility and enhanced nutrient utilization, supported by the bioactive compounds in chicory, which have been reported to promote gastrointestinal health and digestive efficiency (Ismail and Obeidat 2023; Merwe and Brand 2020).

The positive effects of chicory on animal performance are consistent with previous reports describing its role in improving rumen microbial stability, nutrient absorption, immune function, and body weight gain (Abrams et al. 2005; da Silva Dias et al. 2021; Hao et al. 2020; Shiningavamwe et al. 2025; Vogt et al.

2015). In addition, its drought tolerance and high mineral content make chicory a valuable forage resource (Dicksved et al, 2015; Loo, 2007; Nwafor et al. 2017). Combined with its high digestibility and palatability, these characteristics support the use of *Chicory intybus* var. *Chico* as a sustainable substitute for commercial concentrates in sheep fattening systems (Dicksved et al. 2015; Ivarsson et al. 2011, 2012; Niderkorn et al. 2015).

3.6 Practical implications and future directions

Two findings are directly relevant to tropical smallholder sheep production. Harvesting *C. intybus* var. *Chico* at 40 days rather than 60 days yielded a statistically comparable fresh biomass (4.39 vs. 4.91 ton/ha) and an equivalent GHG footprint per unit of biomass, so that the shorter interval can be adopted without a yield or emission penalty. It has been demonstrated that *C. intybus* var. Chico experiences a decline in crude protein and digestibility as harvest is postponed. The 40-day schedule enables farmers to maintain higher levels of nutritional value and incorporate additional cutting cycles into a growing season, thereby increasing the cumulative annual forage supply. For households reliant on forage cultivated on-farm, this constitutes a management change that is cost-free to implement.

The feeding results point the same way. *C. intybus* var. Chico replaced up to 45% of dietary concentrate while feed intake held steady and digestibility, daily gain, and feed conversion all improved. Concentrate is the most expensive part of smallholder sheep rations in Indonesia, so substituting a protein-rich forage grown on-farm lowers cash input while supporting growth. The response was strongest at 35–45% inclusion levels, providing a workable target range for ration formulation where *C. intybus* var. Chico is available.

Several questions remain before these results can guide farm-scale recommendations. The cutting age comparison covered a single regrowth cycle at a single site on a single soil type, so multi-season trials across soils and rainfall patterns, and in other tropical regions, are needed to confirm that these patterns hold under field conditions and repeated defoliation. The feeding trial ran for six weeks on growing males; longer studies that include reproductive females and add carcass and rumen-fermentation measurements would show whether the improvements in growth and feed efficiency persist and carry through to product quality. Pairing *C. intybus* var. Chico inclusion with enteric methane measurement would connect the forage-stage emissions reported here to the animal-stage emissions that dominate the ruminant footprint, giving a fuller life-cycle account. Economic analysis of establishment cost and stand persistence under smallholder management will ultimately decide whether on-farm *C. intybus* var. Chico is a viable substitute for purchased concentrate.

3.7 Limitation

Several limitations bound the interpretation of these findings. The agronomic and emission comparison rested on two cutting ages at a single site, one soil type (regosol), and one regrowth cycle, which constrains how far the results extend beyond this soil and this single cycle. Gas fluxes were measured using static closed chambers in two daily sessions rather than continuously, so short-term diurnal peaks in CO_2 and N_2O may not have been fully captured, and the high variability of the N_2O and CH_4 data limited the power to detect small differences between cutting ages. The feeding trial used 20 growing male sheep over six weeks, with five animals per treatment; the modest replication and short duration limit the detection of smaller treatment effects and provide no information on longer-term performance or reproductive and carcass outcomes. The two components were also run as separate experiments, and the diets used a single *C. intybus* var. Chico batch rather than forage harvested at each cutting age, so the agronomic optimum and the animal responses are linked by inference rather than tested in the same animals. The lower ether extract digestibility at higher *C. intybus* var. Chico inclusion was recorded but not mechanistically resolved, and because rumen fermentation and methane were not measured, the digestive and emission mechanisms behind the performance gains remain to be confirmed.

4 Conclusions

Cutting age and dietary inclusion together set how *C. intybus* var. Chico performs from field to animal. Harvesting at 40 rather than 60 days after regrowth yielded statistically equivalent fresh biomass and an equivalent greenhouse gas footprint per unit of forage, despite higher CO_2 efflux at the earlier stage, so the earlier harvest carries no yield penalty or emission intensity while allowing more frequent cutting at higher expected quality. In the feeding trial, replacing concentrate with *C. intybus* var. Chico up to 45% of the ration held dry matter intake steady and raised crude protein intake, nutrient digestibility, daily gain, and feed efficiency, with the clearest gains at 35 to 45% inclusion. Taken together, the two experiments show that *C. intybus* var. Chico can be harvested on a short cycle and fed as a substantial partial replacement for concentrate without sacrificing productivity or increasing the forage emission cost. For tropical smallholder systems such as Indonesia, where concentrate is costly, and forage quality is uneven, *C. intybus* var. Chico offers a practical, lower-input route to a steadier feed supply and better thin-tailed sheep performance.

Declarations

Conflict of Interest

The authors declare no competing financial interests or personal relationships that could influence this work.

Ethics Statement

All procedures involving animals were reviewed and approved by the Pre-Clinical Research Ethics Commission, Faculty of Veterinary Medicine, Universitas Gadjah Mada, Yogyakarta, Indonesia (Approval No. 0051/EC-FKH-Eks/2020). All animal experiments were conducted in accordance with the relevant institutional guidelines and regulations for the care and use of laboratory animals.

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Author Contribution

NU contributed to conceptualization, investigation, methodology, sample collection, formal analysis, visualization, funding acquisition, writing–review and editing, and finalization of the manuscript; WS, RAP, NIH and MSH contributed to investigation, sample collection, project administration, and writing the original draft. All authors read and approved the final version of the manuscript.

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Data Availability

The data supporting the findings of this study are fully presented within the manuscript. No additional datasets were generated or analyzed beyond those reported in this article.

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Figures

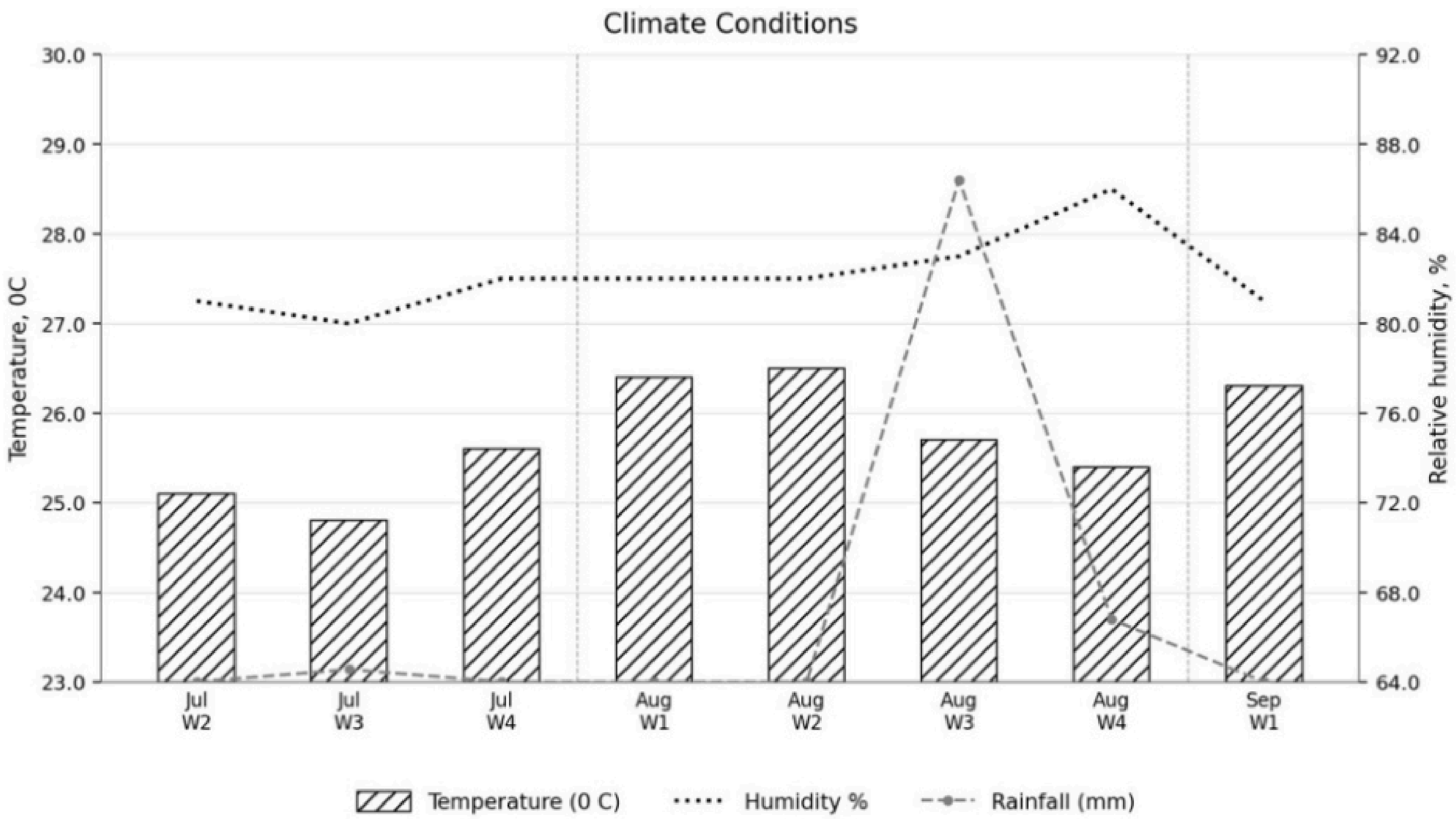

Figure 1

Temperature (°C), relative humidity (%), and rainfall intensities at the study location during the experimental period.