



Research article

Effects of processing methods on nutritive value, cannabinoid profiles and pellet quality of hemp leaf-based feeds

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Abstract

Importance of the work: Industrial hemp (*Cannabis sativa* L.) is a potential alternative feed resource because of its favorable chemical composition and relatively high protein content; however, its use is constrained by variable nutritive value and concerns over cannabinoid residues.

Objectives: To evaluate the chemical composition, nutritive value and cannabinoid concentrations of hemp leaf-based feeds processed as hay, silage and pellets and to compare the hemp pellet formulations prepared with molasses or cassava starch as binders.

Materials and Methods: Hemp leaves were processed into hay, silage and pellets and analyzed for chemical composition, fiber fractions, crude protein and cannabinoids. Hemp leaf pellets with molasses or cassava starch were compared with leucaena [*Leucaena leucocephala* (Lam.) de Wit] leaf pellets. Forage quality indices were calculated: dry matter digestibility (DMD), dry matter intake (DMI) and relative feed value (RFV).

Results: Pellets had the lowest moisture content (5.6%) and the highest dry matter (94.4%). Silage contained the highest cannabidiolic acid (2.27 mg/g), whereas pellets had the highest cannabidiol (7.64 mg/g). Leucaena pellets had higher crude protein (17.2%) but also higher fiber levels. Among the hemp pellet formulations, molasses-bound pellets had the most favorable calculated forage quality indices, with significantly higher estimated DMD (74.96%), predicted DMI (3.34% of body weight) and RFV (193.9), but lower crude protein content.

Main finding: Pelleting hemp leaves, particularly with molasses, improved the calculated forage quality indices and feed-handling potential. However, the reduced crude protein in pellets containing a binder and measurable cannabinoid concentrations indicated that practical use should be restricted to regulated and monitored feeding systems and validated through animal-based studies before commercial application.

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Introduction

The demand for high-quality feeds to support sustainable livestock and dairy/beef production continues to increase, particularly in tropical and subtropical regions where prolonged dry seasons and irregular rainfall restrict year-round access to nutritious roughages with adequate crude protein, fiber and suitable moisture content (Ribeiro et al., 2015; Nunes et al., 2022). Therefore, forage conservation practices, such as haymaking and ensiling, are critical to preserve feed resources, reduce nutrient losses and extend storage life (Kyawt et al., 2020). In addition, pelleting is used widely to increase the bulk density and improve handling and transport, while reducing feed sorting, which may enhance voluntary intake and nutrient utilization in practical feeding systems (Aregheore, 2002; Ribeiro et al., 2015).

Industrial hemp (*Cannabis sativa* L.) leaves have attracted attention as an alternative roughage/feed ingredient because of their favorable nutritional profile and bioactive constituents (Papatzimos and Kasapidou, 2024). Among these, cannabidiol (CBD) is of particular interest because it is a major non-intoxicating cannabinoid in hemp and is especially relevant in leaf- and flower-rich biomass, where cannabinoids may contribute both functional value and safety concerns (Papatzimos and Kasapidou, 2024; Irawan et al., 2025). Commonly, in plant tissues, CBD occurs together with its acidic precursor, cannabidiolic acid (CBDA), with the relative abundance of these compounds possibly shifting during processing and storage. Accordingly, when hemp leaves are considered for feed use, CBD is relevant not only as a bioactive constituent but also in relation to residue risk, regulatory compliance and cannabinoid transfer into animal-derived products (Irawan et al., 2025; Fritz et al., 2025).

Furthermore, recent literature has highlighted the need to explicitly consider CBD in livestock-feed research. A recent review concluded that although hemp by-products may offer nutritional potential for ruminants, their broader use remains constrained by residual cannabinoids, particularly THC and CBD, as well as by inconsistent regulatory frameworks among countries (Irawan et al., 2025). In addition, cattle studies have shown that hemp exposure can result in detectable cannabinoid residues in tissues, including CBD, even when overt adverse effects are limited (Fritz et al., 2025). The 2026 EFSA update on the safety of cannabidiol as a novel food, although focused on human food safety, further indicated that CBD safety assessment remains under active evaluation and

still involves unresolved data gaps (European Food Safety Authority, Nutrition, Novel Foods and Food Allergens Panel, 2026). Together, these findings support the need to evaluate both nutritive characteristics and cannabinoid profiles when developing hemp leaf-based feeds (Irawan et al., 2025; Fritz et al., 2025; European Food Safety Authority, Nutrition, Novel Foods and Food Allergens Panel, 2026; Irawan et al., 2026).

However, information remains limited on the biological effects of CBD in livestock, particularly with respect to safe intake thresholds and the potential carryover of cannabinoids into animal-derived products. Recent studies have shown that hemp-derived feeds can result in measurable transfer of cannabinoids into milk and edible tissues under some feeding conditions (Wagner et al., 2022; Fritz et al., 2025), although the extent of transfer depends on the cannabinoid profile, feed matrix and exposure level (Irawan et al., 2025). In dairy cows, feeding cannabinoid-rich hemp silage was associated with detectable transfer of cannabinoids into milk and adverse effects on animal health and performance (Wagner et al., 2022), whereas studies using spent hemp biomass in dairy cows and beef steers generally reported minimal adverse effects under the tested conditions, despite measurable cannabinoid residues in some tissues (Irawan et al., 2024; Irawan et al., 2026). Overall, these findings indicate that the practical use of hemp leaf-based feeds requires evaluation not only of nutritive value but also of cannabinoid safety, residue carryover and regulatory acceptability (Irawan et al., 2025). In addition to safety concerns, the legal status of hemp-derived materials in animal feeding systems varies substantially among jurisdictions. Therefore, permission to cultivate industrial hemp does not necessarily imply approval for the use of hemp leaves or cannabinoid-containing materials in animal feed; practical application must be considered within the specific regulatory framework of each country.

Processing conditions further influence cannabinoid stability and transformation. Ensiling can modify substantially cannabinoid profiles during storage, including marked reductions in acidic cannabinoid forms under practical conditions (Klevenhusen et al., 2024); feeding hemp silage to lactating cows has been associated with detectable cannabinoids in milk (Wagner et al., 2022). Recent reviews have emphasized that hemp by-products have potential as feed resources; however, robust control of cannabinoid concentrations is essential for safe adoption (Altman et al., 2024; Papatzimos and Kasapidou, 2024).

Pelleting hemp leaf-based feeds is a practical option to improve storage, transport and the physical feed quality, while

binder inclusion (molasses, cassava starch) can enhance pellet durability, hardness and density (Matkowski et al., 2020; Gopar et al., 2022). In addition, plant-based binders may affect pellet physical traits and digestibility outcomes (Jaelani et al., 2024). However, available evidence is still largely based on studies addressing specific materials or single processing pathways rather than direct comparisons of nutritive value and cannabinoid profiles across hay, silage and pellets within the same experimental framework (Kleinhenz et al., 2020; Krebs et al., 2021; Wagner et al., 2022; Klevenhusen et al., 2024). Likewise, direct comparisons remain scarce of hemp leaf pellet quality across binder types, together with standardized nutritive indices such as dry matter digestibility (DMD), dry matter intake (DMI) and relative feed value (RFV) (Rohweder et al., 1978; Matkowski et al., 2020; Gopar et al., 2022; Jaelani et al., 2024; Altman et al., 2024).

Therefore, the current study aimed: 1) to evaluate the chemical composition, nutritive value and cannabinoid profiles of hemp leaf-based feeds processed as hay, silage, or pellets; and 2) to develop and compare pellet formulations using different binders, with a comparative benchmark against pellets produced from *Leucaena leucocephala*. The findings should clarify both the potential and constraints of hemp leaves as a feed resource and inform practical processing approaches for safe and sustainable integration into livestock feeding systems.

Materials and Methods

Procurement of hemp material and study site

Hemp plant material was obtained through collaboration with the Thai Federal Hemp Corporation, a legally licensed company for hemp cultivation and distribution in Chiang Mai Province, Thailand. The hemp cultivar code 14-2 was grown at the Doi Pui Research Station (Suan Song Saen), Suthep Sub-district, Mueang Chiang Mai District, Chiang Mai Province, Thailand (18°48'40.4"N, 98°52'58.6"E), at an average elevation of 1,272 m above mean sea level. The soil growing medium was classified as the Doi Pui soil series, characterized as a deep red loam with high organic matter content and high inherent fertility. The site has an average annual rainfall of approximately 1,600 mm and a mean annual temperature of 16°C.

Hemp plants were harvested at the flowering to early seed-development stage, approximately 120–130 d after planting, corresponding to the reproductive period commonly associated

with hempseed production (Alberta Agriculture and Forestry, 2017; Arnall et al., 2019). Then, whole plants were sampled randomly from the field and transported to the laboratory at the Department of Agronomy, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Nakhon Pathom Province, Thailand, for use as raw material in subsequent experiments.

Preparation of feed samples and experimental design

The experiment was arranged in a completely randomized design (CRD) with four replications. Hemp leaves (residual biomass from a legally authorized production area in Chiang Mai Province, Thailand; certified seed source) were processed into three feed forms (hay, silage, pellets). Before allocating treatments, the collected hemp leaf material for each processing method was mixed thoroughly to obtain a homogeneous bulk sample; then, subsamples were assigned randomly into four independent replicates. Thus, the experimental unit for each processing method was the randomly assigned replicate prepared from the homogenized bulk material. Pellet physical quality was evaluated further by comparing binder treatments in the hemp pellets with the pellets produced from leucaena leaf meal (*Leucaena leucocephala* (Lam.) de Wit).

For the hay preparation, hemp leaves were sun-dried and turned daily for 3–4 d to ensure uniform drying to $\leq 15\%$ moisture content and then stored in mesh bags in a well-ventilated shed.

For the silage preparation, fresh hemp leaves (approximately 2 kg) were chopped into 0.5–1.0 cm length pieces and mixed thoroughly to obtain a homogeneous material. Then, the mixed material was randomly divided into four replicates. For each replicate, the chopped leaves were packed into plastic silage bags, the openings were tightly sealed and the bags were stored under anaerobic conditions. Ensiling was carried out for 30 d. Fermentation was considered complete when the pH had declined and stabilized; after 30 d, the silage reached a stable pH of 5.7.

For the pellet preparation, molasses and cassava starch were used as binders at 1:6 and 1:10 (w/w; binder-to-hemp leaf meal), respectively, with a no-binder control. Dried hemp leaves (95°C, 72 h) were ground and passed through a 1 mm screen, mixed with binder and pelleted using a 6 mm $\times$ 40 mm die. The pellets were stored in airtight containers until analysis. In addition to the unbound hemp leaf pellets, pellet formulations containing molasses or cassava starch were prepared and subsequently characterized for moisture content,

dry matter, chemical composition, cannabinoid concentrations and calculated forage quality indices. These analyses were conducted to compare the effects of binder inclusion on the properties of dried hemp leaf pellets. For pellet evaluation, each pellet formulation was prepared in four independent replicate batches, with each batch regarded as an experimental unit for statistical analysis.

Prior to analyses, all feed samples were oven-dried (95°C, 72 h) to determine the dry matter (DM) and moisture contents, then ground and passed through a 1 mm screen and stored in airtight containers before chemical composition, nutritive value and cannabinoid analyses.

Nutritive value and chemical composition analyses

Representative samples from each processing method were collected randomly for nutritive and chemical composition analyses consisting of crude protein (CP), ash and detergent fiber fractions (neutral detergent fiber, NDF; acid detergent fiber, ADF; and acid detergent lignin, ADL). Hemicellulose and cellulose were calculated from detergent fiber relationships, while lignin was expressed as ADL.

Crude protein was determined using the Kjeldahl method as total nitrogen (%N) $\times$ 6.25. The ash content was measured according to Association of Official Analytical Chemists (1990) by combusting samples at high temperature until organic matter was completely removed. Fiber fractions (NDF, ADF and ADL) were analyzed by sequential detergent analysis using an ANKOM 200 Fiber Analyzer (ANKOM Technology Corp.; Fairport, NY, USA). Hemicellulose and cellulose were calculated using Equations 1–2 (Van Soest et al., 1991):

$$\text{Hemicellulose} = \text{NDF} - \text{ADF} \quad (1)$$

$$\text{Cellulose} = \text{ADF} - \text{ADL} \quad (2)$$

Cannabinoid analysis

Finely ground samples from each processing method were analyzed for cannabinoids using high-performance liquid chromatography with ultraviolet detection (HPLC–UV) following the Association of Official Analytical Chemists Official Method 2018.10 (Mudge and Brown, 2020), with detection at 240 nm.

For extraction, approximately 200 mg of dried sample were mixed with 25 mL methanol, sonicated for 15 min, centrifuged (4,500 revolutions per minute for 2 min) and filtered through a 0.22 μm nylon membrane into 2 mL HPLC

vials. In total, 11 cannabinoids were quantified, including cannabidiol (CBDV), cannabidiolic acid (CBDA), cannabigerolic acid (CBGA), cannabigerol (CBG), cannabidiol (CBD), tetrahydrocannabivarin (THCV), cannabinol (CBN), delta-9-tetrahydrocannabinol (Δ 9-THC), delta-8-tetrahydrocannabinol (Δ 8-THC), cannabichromene (CBC), and tetrahydrocannabinolic acid (THCA), using certified reference standards and calibration curves. The concentrations were calculated from peak areas. Method performance (accuracy, precision, linearity, retention time consistency) was verified according to Association of Official Analytical Chemists criteria and the results were reported as milligram per gram of DM.

Based on method sensitivity and published validations under similar analytical conditions, the estimated limit of detection (LOD) and quantification (LOQ) values were approximately 0.001–0.01 and 0.003–0.03 mg/g DM, respectively. Therefore, compounds reported as not detected (ND) were interpreted as being present at concentrations below the LOQ.

Evaluation of nutritive quality of hemp leaf pellets

The nutritive quality of the pellets produced from the hemp leaves was assessed using calculated forage quality indices: dry matter digestibility (DMD), dry matter intake (DMI) and relative feed value (RFV), according to Rohweder et al. (1978). These indices were derived from ADF and NDF concentrations rather than from direct animal feeding or digestibility measurements. DMD and DMI were estimated from ADF and NDF contents, respectively and the resulting values were used to calculate RFV, using Equations 3–5:

$$\text{DMD (\%)} = 88.9 - (0.779 \times \text{ADF\%}) \quad (3)$$

$$\text{DMI (\% of body weight)} = 120 / \text{NDF\%} \quad (4)$$

$$\text{RFV} = (\text{DMD} \times \text{DMI}) / 1.29 \quad (5)$$

The calculated RFV values were used as standardized indices for comparing relative forage quality among pellet formulations.

Statistical analysis

All data were analyzed using analysis of variance (ANOVA) for a completely randomized design (CRD) with the Statistix 8.0 software (Analytical Software; Tallahassee, FL, USA), with each replicate considered an experimental unit. Treatment was treated as a fixed effect because the objective was to

compare the specific processing methods or pellet formulations included in the study. Before final interpretation, residuals from the ANOVA model were examined to evaluate the adequacy of model assumptions, including approximate normality and homogeneity of variance, using normal probability plots and plots of residuals versus fitted values. In addition, the data were checked for outliers and consistency among replicates. When the overall ANOVA indicated a significant treatment effect, means were separated using the least significant difference (LSD) test at the $p < 0.05$ probability level. The LSD test was retained because the experiment followed a simple and balanced design with equal replication across treatments, with mean comparisons performed only after a significant overall F-test. The results were presented as mean $\pm$ standard deviation (SD).

Results

Chemical composition and nutritive value of hemp leaves processed as hay, silage and pellets

Fig. 1 shows that the moisture content (Fig. 1A) and the DM content (Fig. 1B) differed highly significantly among the three hemp leaf feed forms ($p < 0.01$). Hay had the highest moisture content (10.2%), followed by silage (6.5%), whereas pellets had the lowest (5.6%). In contrast, the DM content displayed the opposite pattern, with the pellets having the greatest DM content (94.4%), followed by the silage (93.5%) and the hay (89.7%). Based on these results, pelleting reduced the moisture content and increased the proportion of DM more effectively than haymaking or ensiling. Subsequently, the DM values obtained were used as the basis for further analyses of chemical composition, nutritive value and cannabinoid concentrations.

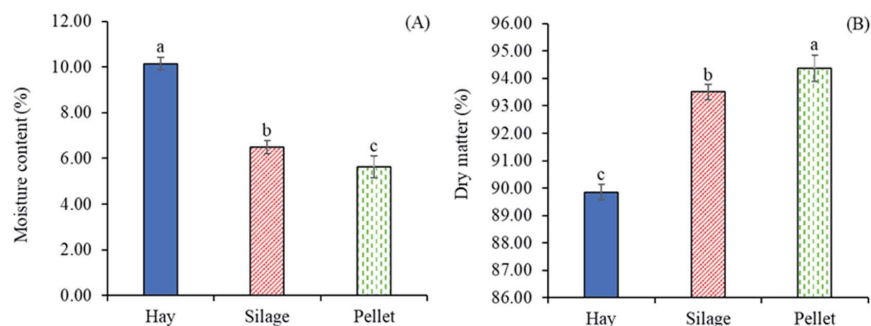


Fig. 1 Moisture content (A) and dry matter (B) of three hemp leaf-based feed types (hay, silage, pellets). Different lowercase letters above the bars indicate significant differences according to the least significant difference (LSD) test. Error bars indicate $\pm$ SD.

Fig. 2 shows that the chemical composition and nutritive value of the hemp leaves processed as hay (dried hemp leaves), silage and pellets. There were highly significant differences among the processing methods ($p < 0.01$) for all measured components: NDF, ADF, hemicellulose, cellulose, lignin, ash and CP, thereby allowing direct comparisons of the nutritional characteristics of the dried hemp leaves and hemp leaf silage with those of pellets. The NDF content (Fig. 2A) was the highest in the silage (46.2%), intermediate in the hay (43.5%) and the lowest in the pellets (38.7%). ADF (Fig. 2B) was the highest in the hay (29.2%), followed by the silage (27.3%) and was lowest in the pellets (19.8%).

For the calculated structural carbohydrates, hemicellulose (Fig. 2C) was high in both the silage (18.9%) and pellets (18.7%), with no significant difference between them, while the hay had the lowest hemicellulose (15.6%). Cellulose (Fig. 2D) was highest in the hay (13.4%), followed by the pellets (12.0%) and lowest in the silage (10.3%). Lignin (Fig. 2E) was the highest in the silage (9.2%), whereas the hay (3.2%) and pellets (2.5%) were lower and did not differ significantly from each other. The ash content (Fig. 2F) was highest in the hay (12.8%), followed by the silage (9.1%) and lowest in pellets (6.5%).

The crude protein (CP; Fig. 2G) differed markedly among processing methods, being highest in the silage (19.7%), intermediate in the hay (15.1%) and lowest in the pellets (12.3%). Overall, based on these results, the processing method substantially altered fiber fractions, protein concentration and mineral (ash) content, thereby influencing the nutritive value of the hemp leaf-based feeds.

Cannabinoid concentrations in hemp leaf-based feeds

Table 1 presents the cannabinoid concentrations in the

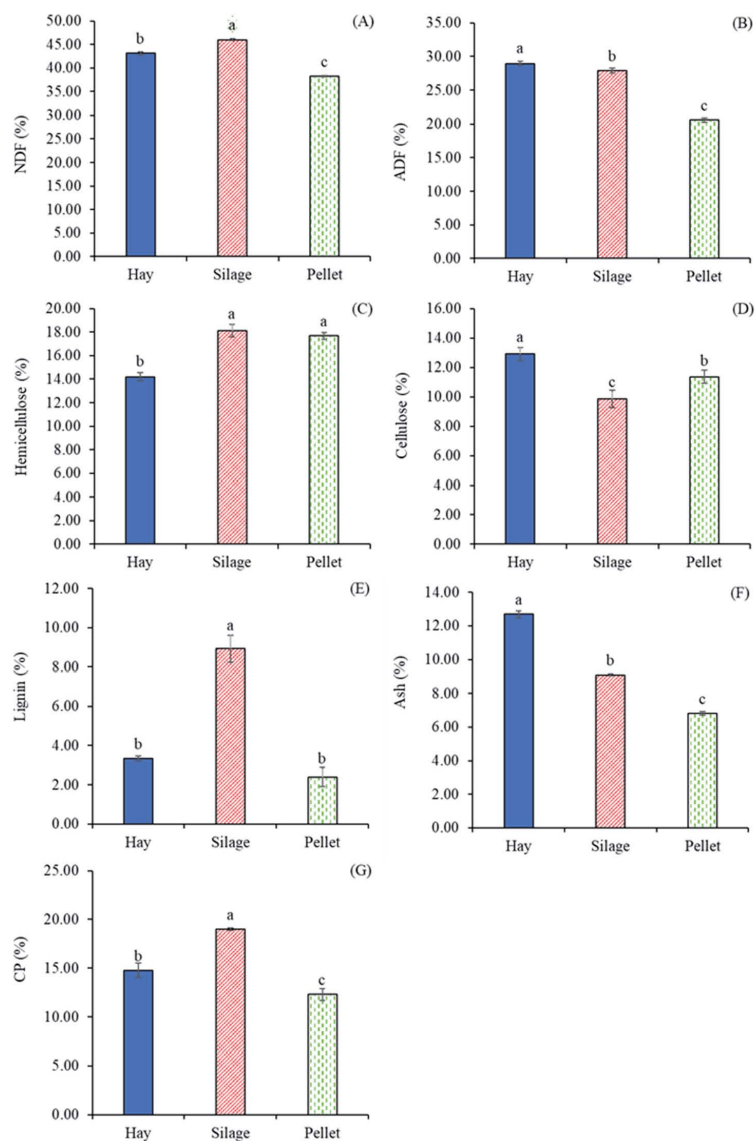


Fig. 2 Chemical composition of hemp leaves processed as hay (dried hemp leaves), silage and pellets: (A) neutral detergent fiber (NDF); (B) acid detergent fiber (ADF); (C) hemicellulose (C); (D) cellulose; (E) lignin; (F) ash; (G) crude protein (CP). Different lowercase letters above the bars indicate significant differences according to the least significant difference (LSD) test. Error bars indicate $\pm$ SD.

hemp leaf-based feeds processed as hay, silage and pellets. There were significant differences among the processing methods for several cannabinoids.

Among the acidic cannabinoids, CBDA was the highest in silage (2.27 mg/g DM), followed by the hay (1.28 mg/g DM), whereas it was not detected in the pellets. In contrast, CBD was the greatest in the pellets (7.64 mg/g DM), followed by the silage (6.55 mg/g DM) and hay (4.02 mg/g DM), indicating a clear processing effect. In addition, CBN was the highest in the pellets (2.31 mg/g DM), intermediate in the hay (2.05 mg/g DM) and the lowest in the silage (1.85 mg/g DM). CBGA,

CBG and THCV were not detected in any of the three feed forms.

Within the tetrahydrocannabinol-related compounds, Δ^9 -THC was the highest in the silage (3.85 mg/g DM), followed by the hay (3.43 mg/g DM) and pellets (2.40 mg/g DM). Similarly, THCA was the highest in the silage (2.09 mg/g DM), followed by the hay (1.80 mg/g DM) and pellets (1.47 mg/g DM). Δ^8 -THC was detected only in the silage (2.15 mg/g DM), while CBC did not differ among the feed forms (mean 1.12 mg/g DM).

Considering the summed indices, total CBD was the

Table 1 Cannabinoid contents of three hemp leaf-based feed types (hay, silage and pellets).

Feed type	CBDV (mg/g DM)	CBDA (mg/g DM)	CBGA (mg/g DM)	CBG (mg/g DM)	CBD (mg/g DM)	THCV (mg/g DM)	CBN (mg/g DM)
Hay	ND	1.28±0.06 ^b	ND	ND	4.02±0.01 ^c	ND	2.05±0.01 ^b
Silage	ND	2.27±0.02 ^a	ND	ND	6.55±0.08 ^b	ND	1.85±0.01 ^c
Pellet	ND	ND	ND	ND	7.64±0.50 ^a	ND	2.31±0.02 ^a
F-test	NA	**	NA	NA	**	NA	**
Mean	NA	1.78	NA	NA	6.07	NA	2.07
CV	NA	3.56	NA	NA	6	NA	1.75
	Δ ⁹ -THC (mg/g DM)	Δ ⁸ -THC (mg/g DM)	THCA (mg/g DM)	CBC (mg/g DM)	Total CBD (mg/g DM)	Total THC (mg/g DM)	
Hay	3.43±0.08 ^b	ND	1.80±0.05 ^b	1.11±0.01	5.14±0.12 ^c	5.00±0.05 ^b	
Silage	3.85±0.05 ^a	2.15±0.12	2.09±0.02 ^a	1.14±0.02	8.54±0.08 ^a	7.81±0.10 ^a	
Pellet	2.40±0.03 ^c	ND	1.47±0.01 ^c	1.11±0.01	7.64±0.04 ^b	3.69±0.50 ^c	
F test	**	NA	**	ns	**	**	
Mean	3.22	NA	1.78	1.12	7.11	5.5	
CV	2.35	NA	2.82	1.31	5.39	2.21	

CBDV = cannabidiavarin; CBDA = cannabidiolic acid; CBGA = cannabigerolic acid; CBG = cannabigerol; CBD = cannabidiol; THCV = tetrahydrocannabivarin; CBN = cannabinol; CBC = cannabichromene; Δ⁸-THC = Δ⁸-tetrahydrocannabinol; Δ⁸-THC = Δ⁹-tetrahydrocannabinol; THCA = tetrahydrocannabinolic acid; NA = not applicable.

Mean±SD within each column followed by different lowercase superscript letters, are significantly different according to least significant difference test. ns = not significant ($p \geq 0.05$); ** = highly significant ($p < 0.01$); ND = not detected (below limit of quantification).

highest in the silage (8.54 mg/g DM), followed by the pellets (7.64 mg/g DM) and hay (5.14 mg/g DM). Total THC was also the highest in the silage (7.81 mg/g DM), followed by the hay (5.00 mg/g DM) and pellets (3.69 mg/g DM).

Overall, based on these results, the processing method significantly influenced cannabinoid composition. The silage tended to have the highest concentrations of THC-related compounds and total cannabinoids, whereas the pelleting was associated with the greatest CBD concentration and the hay had intermediate values relative to the other processing methods.

Chemical composition and calculated nutritive quality of dried hemp leaf pellet formulations with different binders

Fig. 3 presents the moisture content (Fig. 3A) and DM (Fig. 3B) contents of the pellets produced from the leucaena leaves (Leucaena), the hemp leaves (Hemp), the hemp leaves with molasses (Hemp + Molasses) and the hemp leaves with cassava starch (Hemp + Starch). There were significant differences among the pellet formulations. The moisture content was the highest in Hemp + Molasses (6.1%), followed by Hemp (5.6%)

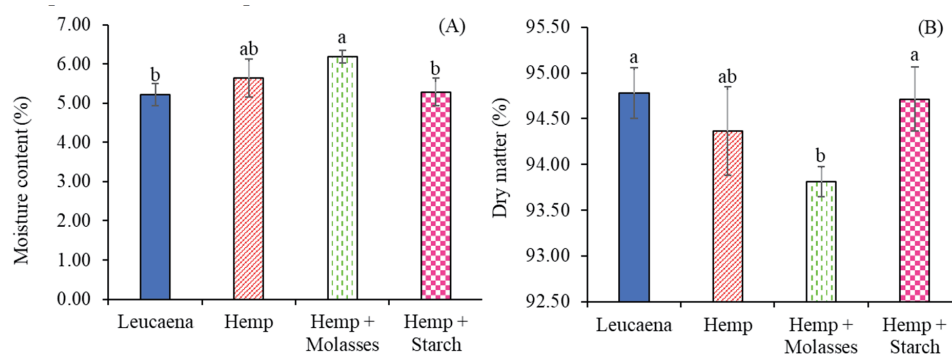


Fig. 3 Compositional properties of pelleted feeds prepared from leucaena leaves, hemp leaves, hemp leaves with molasses as a binder and hemp leaves with cassava starch as a binder: (A) moisture content; (B) dry matter content. Different lowercase letters above the bars indicate significant differences according to the least significant difference (LSD) test. Error bars indicate ± SD.

and Hemp + Starch (5.3%), whereas Leucaena had the lowest value (5.2%).

The DM contents were the highest in Leucaena (94.7%) and Hemp + Starch (94.7%) and did not differ significantly, followed by Hemp (94.4%), while Hemp + Molasses had the lowest DM content (93.7%). Based on these results, binder inclusion influenced the pellet moisture and DM contents, particularly with molasses, which increased its moisture content and reduced its DM contents, whereas cassava starch did not decrease the DM content compared to Leucaena pellets.

Table 2 presents the chemical composition and nutritive value of pellets produced from Leucaena, Hemp, Hemp + Molasses and Hemp + Starch, thereby characterizing dried hemp leaf pellets and the corresponding formulations prepared with molasses or cassava starch as binders. There were highly significant differences among the formulations for all measured components ($p < 0.01$). NDF was the highest in the Leucaena pellets (51.13%), followed by Hemp (38.27%) and Hemp + Starch (37.50%), while the lowest NDF was in Hemp + Molasses (33.74%). There was a similar pattern for ADF, with the highest value in Leucaena (36.22%) and the lowest in Hemp + Molasses (16.78%).

Hemicellulose was the highest in Hemp + Starch (18.19%), followed by Hemp (17.69%) and Hemp + Molasses (16.96%), whereas Leucaena had the lowest hemicellulose content (14.91%). Cellulose was the highest in Leucaena (21.41%) and the lowest in Hemp + Molasses (9.97%). The lignin content was the highest in Leucaena (5.14%), followed by Hemp + Starch (2.51%) and Hemp (2.40%), while Hemp + Molasses had the lowest lignin (0.33%). The ash content was the highest in Leucaena (9.68%) and the lowest in Hemp + Starch (5.86%).

The CP content was the highest in the Leucaena (17.18%), followed by Hemp (12.30%), whereas Hemp + Starch (10.07%) and Hemp + Molasses (9.56%) were clearly lower. Overall, the Leucaena pellets contained higher fiber fractions and CP contents than the hemp-based formulations. Adding binders, such as molasses and cassava starch, reduced some fiber fractions; however, this was accompanied by a reduction in the CP concentration, indicating a trade-off between reduced fiber fractions and lower crude protein concentration. In particular, although the molasses-bound formulation subsequently had the highest estimated DMD, predicted DMI and RFV, its CP content (9.56%) was lower than that of Hemp pellets without binder (12.30%) and Leucaena pellets (17.18%).

Cannabinoid characterization of dried hemp leaf pellet formulations with different binders

Table 3 presents the cannabinoid profiles of the pellets produced from hemp leaf meal (Hemp), hemp leaf meal with molasses (Hemp + Molasses) and hemp leaf meal with cassava starch (Hemp + Starch). There were significant differences among the formulations for some cannabinoids (some at $p < 0.05$ and some at $p < 0.01$).

Most cannabinoids (CBDV, CBDA, CBGA, CBG, THCV) were not detected in any pellet formulation. In contrast, CBD differed markedly among treatments, with the highest concentration in Hemp pellets (7.64 mg/g), followed by Hemp + Starch (7.02 mg/g) and the lowest in Hemp + Molasses (6.29 mg/g). For CBN, the highest concentration was in Hemp pellets (2.54 mg/g), whereas the lowest was in Hemp + Molasses (1.93 mg/g).

Table 2 Chemical composition and nutritive value of pelleted feeds prepared from leucaena leaves, hemp leaves, hemp leaves with molasses as a binder and hemp leaves with cassava starch as binder

Pelleted feed	NDF (%)	ADF (%)	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Ash (%)	CP (%)
Leucaena	51.13±0.41 ^a	36.22±0.42 ^a	14.91±0.47 ^c	21.41±0.76 ^a	5.14±0.32 ^a	9.68±0.11 ^a	17.18±0.18 ^a
Hemp	38.27±0.15 ^b	20.59±0.33 ^b	17.69±0.28 ^{ab}	11.37±0.46 ^b	2.40±0.50 ^b	6.82±0.10 ^b	12.30±0.61 ^b
Hemp + Molasses	33.74±0.46 ^d	16.78±0.20 ^d	16.96±0.57 ^b	9.97±0.23 ^c	0.33±0.14 ^c	6.48±0.07 ^c	9.56±0.64 ^d
Hemp + Starch	37.50±0.45 ^c	19.30±0.37 ^c	18.19±0.52 ^a	10.93±0.37 ^b	2.51±0.12 ^b	5.86±0.08 ^d	10.07±0.64 ^c
F test	**	**	**	**	**	**	**
Mean	41.05	24.53	16.52	14.25	2.62	7.66	13.01
CV	1.12	1.7	3.23	4.25	13.77	1.5	5.18

NDF = neutral detergent fiber, ADF = acid detergent fiber, CP = crude protein.

Mean±SD within the same column followed by different lowercase superscript letters are significantly different according to least significant difference test ($p < 0.05$).

** = highly significant ($p < 0.01$).

Table 3 Cannabinoid contents of pelleted feeds prepared from hemp leaves, hemp leaves with molasses as a binder and hemp leaves with cassava starch as a binder

Feed type	CBDV (mg/g DM)	CBDA (mg/g DM)	CBGA (mg/g DM)	CBG (mg/g DM)	CBD (mg/g DM)	THCV (mg/g DM)	CBN (mg/g DM)
Hemp	ND	ND	ND	ND	7.64±0.43 ^a	ND	2.54±0.40 ^a
Hemp + Molasses	ND	ND	ND	ND	6.29±0.11 ^c	ND	1.93±0.03 ^b
Hemp + Starch	ND	ND	ND	ND	7.02±0.16 ^b	ND	2.11±0.05 ^b
F-test	NA	NA	NA	NA	**	NA	*
Mean	NA	NA	NA	NA	6.99	NA	2.19
CV	NA	NA	NA	NA	4.51	NA	12.2
	Δ9-THC (mg/g DM)	Δ ⁸ -THC (mg/g DM)	THCA (mg/g DM)	CBC (mg/g DM)	Total CBD (mg/g DM)	Total THC (mg/g DM)	
Hemp	2.53±0.04 ^a	ND	1.47±0.04	1.11±0.01	7.64±0.43 ^a	3.69±0.07 ^b	
Hemp + Molasses	2.40±0.07 ^b	2.11±0.50	1.62±0.25	1.08±0.04	6.29±0.11 ^c	5.54±0.99 ^a	
Hemp + Starch	2.52±0.03 ^a	ND	1.51±0.05	1.09±0.01	7.02±0.16 ^b	3.85±0.07 ^b	
F test	*	NA	ns	ns	**	**	
Mean	2.49	NA	1.53	1.09	6.99	4.36	
CV	2.36	NA	11.2	2.67	4.51	15.3	

DM = dry matter; CBDV = cannabidiol; CBDA = cannabidiolic acid; CBGA = cannabigerolic acid; CBG = cannabigerol; CBD = cannabidiol; THCV = tetrahydrocannabivarin; CBN = cannabinol; CBC = cannabichromene; Δ⁸-THC = Δ⁸-tetrahydrocannabinol; Δ9-THC = Δ9-tetrahydrocannabinol; THCA = tetrahydrocannabinolic acid; NA = not applicable.

Mean±SD within the same column followed by different lowercase superscript letters are significantly different according to least significant difference test ($p < 0.05$).

ns = not significant ($p \geq 0.05$); ** = highly significant ($p < 0.05$); ND = not detected (below limit of quantification).

Within the tetrahydrocannabinol-related compounds, Δ9-THC concentrations were similar between Hemp (2.53 mg/g) and Hemp + Starch (2.52 mg/g) and were significantly higher than Hemp + Molasses (2.40 mg/g). Δ8-THC was detected only in Hemp + Molasses (2.11 mg/g), whereas THCA and CBC did not differ among formulations (means of 1.53 and 1.09 mg/g, respectively).

Considering the summed indices, the total CBD was the highest in Hemp pellets (7.64 mg/g), followed by Hemp + Starch (7.02 mg/g) and the lowest in Hemp + Molasses (6.29 mg/g). In contrast, the total THC was the highest in Hemp + Molasses (5.54 mg/g) and the lowest in Hemp pellets (3.69 mg/g).

Overall, based on these results, binder inclusion during pelleting, particularly with molasses, altered the cannabinoid composition by increasing the total THC, while decreasing the total CBD and CBN compared to the pellets produced from hemp leaves alone.

Evaluation of nutritive quality indices of hemp leaf-based pellet feeds

Table 4 show the calculated nutritive quality indices of pellets produced from leucaena leaves (Leucaena), hemp leaves (Hemp), hemp leaves with molasses as a binder (Hemp + Molasses) and hemp leaves with cassava starch as a binder (Hemp + Starch). These indices were derived from

Table 4 Calculated forage quality indices (dry matter digestibility, dry matter intake and relative feed value) of pelleted feeds prepared from leucaena leaves, hemp leaves, hemp leaves with molasses as a binder and hemp leaves with cassava starch as a binder.

Pelleted feed	DMD (%)	DMI (%)	RFV
Leucaena	59.13±0.33 ^d	2.22±0.02 ^d	101.97±1.24 ^d
Hemp	71.91±0.26 ^c	2.96±0.01 ^c	164.96±1.15 ^c
Hemp + Molasses	74.96±0.16 ^a	3.34±0.05 ^a	193.93±2.67 ^a
Hemp + Starch	73.02±0.29 ^b	3.03±0.04 ^b	171.66±2.44 ^b
F test	**	**	**
Mean	69.75	2.89	158.13
CV	0.47	1.28	1.37

DMD = dry matter digestibility; DMI = dry matter intake, expressed as % of body weight; RFV = relative feed value. ** = highly significant ($p < 0.01$)

fiber fractions and were used as comparative indicators of forage quality. Significant differences were observed among formulations ($p < 0.01$).

The estimated DMD was the highest in Hemp + Molasses (74.96%), followed by Hemp + Starch (73.02%) and Hemp (71.91%), whereas *Leucaena* had the lowest value (59.13%). A similar pattern was observed for predicted DMI, with the highest value in Hemp + Molasses (3.34% of body weight), followed by Hemp + Starch (3.03%), Hemp (2.96%) and the lowest in *Leucaena* (2.22%). Likewise, RFV was the highest in Hemp + Molasses (193.93), followed by Hemp + Starch (171.66) and Hemp (164.96), while *Leucaena* had the lowest RFV (101.97).

Overall, based on these results, using molasses or cassava starch as binders improved the calculated nutritive quality indices of the hemp leaf-based pellets, with the molasses-based formulation providing the highest predicted digestibility, intake potential and relative feed value among the formulations evaluated. However, the improved calculated forage quality indices for the molasses-bound pellets should be interpreted together with the lower CP concentration of this formulation, indicating that enhancement of predicted digestibility and intake potential was accompanied by a reduction in the protein content.

Discussion

This study demonstrated that processing hemp leaves into hay, silage and pellets markedly changed the moisture and DM contents, the chemical composition and the cannabinoid profiles. The lower moisture and higher DM contents in the pellets are advantageous for storage and handling because reduced water availability can limit microbial activity, heating, spoilage and DM losses during conservation and feed-out (McDonald et al., 1991; Borreani et al., 2018). Therefore, expressing the feed composition on a DM basis was essential for comparing processing methods, as differences in water content can dilute nutrient concentrations and obscure treatment effects (National Academies of Sciences, Engineering and Medicine, 2021). The relatively high final pH of the silage should be interpreted within the specific context of hemp leaf material and the ensiling conditions used in this study, rather than as a general target value for silage quality.

Pelleting and binder inclusion reduced the measured NDF and ADF values, which explains the higher estimated DMD, predicted DMI and RFV values because these indices

are calculated directly from ADF and NDF concentrations (Rohweder et al., 1978). Thus, the higher RFV of the pellets containing a binder indicated improved calculated forage quality indices rather than a confirmed improvement in animal intake, digestibility, or performance. Among the formulations, the molasses-bound pellets had the highest calculated indices but also the lowest crude protein concentration, indicating a clear trade-off between improved predicted digestibility/intake potential and reduced protein density. Therefore, binder use should be optimized not only for pellet quality and calculated forage value but also for the protein requirements of the target animal.

Processing also altered the cannabinoid composition. The high CBDA concentration in the silage, together with the non-detection of CBDA and the high CBD concentration in pellets, suggests that heat exposure during drying and pellet manufacture may have promoted partial decarboxylation of acidic cannabinoids, such as CBDA to CBD and THCA to THC (Wang et al., 2016). In addition, cannabinoid profiles may continue to change during storage through oxidation, degradation, or further conversion under exposure to light, oxygen, temperature and humidity (Kosović et al., 2021; Franco et al., 2022; Bini et al., 2024). Consequently, the cannabinoid concentrations in the hemp leaf-based feeds should be evaluated after processing and during storage, particularly when feeds are intended for practical use.

From a safety and regulatory perspective, the THC-related compounds and CBD remain important constraints for hemp-derived feeds. Studies have shown that cannabinoids can be transferred into milk or retained in edible tissues under some feeding conditions (Krebs et al., 2021; Wagner et al., 2022; Fritz et al., 2025). Although CBD is non-intoxicating, livestock-specific safe intake thresholds have not been clearly established and animal responses appear to depend on the total cannabinoid profile, intake level, exposure duration, feed matrix and target species (Irawan et al., 2025). Furthermore, regulatory requirements vary among jurisdictions; therefore, crop-level definitions of industrial hemp should not be interpreted as automatic approval for feed use. Practical application must comply with local feed regulations, including restrictions on hemp plant parts, cannabinoid limits and residue safety requirements (European Union, 2021; Department of Livestock Development, 2022; FDA, 2026; European Commission, 2026).

For livestock-feeding practice, based on the current results, hemp leaf pellets may be considered only as a potential feed ingredient rather than as a ready-to-use commercial

feed. Before adoption, each production batch should be tested for THC, CBD and other relevant cannabinoids, with their inclusion levels being determined according to the nutritional requirements and legal status for the intended animal species. The molasses-bound formulation may be useful where improved pellet handling and higher calculated forage quality indices are desired; however, its lower CP content means that protein supplementation or reformulation may be needed. Use in milk- or meat-producing animals should be approached cautiously until feeding trials have confirmed animal performance, residue safety, withdrawal considerations and compliance with commercial production standards.

Overall, pelleting appears promising for improving the handling characteristics and calculated nutritive quality indices of hemp leaf-based feeds; however, cannabinoid control remains essential for food-chain safety and regulatory compliance. The main limitation of the current study was that it was based on laboratory analyses and calculated forage quality indices, without *in vivo* feeding trials, *in vitro* digestibility testing, or ruminal fermentability assessment. Therefore, future work should include controlled animal-feeding trials, *in vitro* gas production or digestibility assays, long-term cannabinoid stability tests under realistic storage conditions and process optimization to produce nutritionally balanced pellets with cannabinoid concentrations that remain within jurisdiction-specific compliance limits (Altman et al., 2024; Irawan et al., 2025).

Conclusion

Processing methods substantially affected the chemical composition, cannabinoid profiles and calculated forage quality indices of the tested hemp leaf-based feeds. Pelleting reduced the moisture content and increased the DM content, while binder inclusion, particularly with molasses, improved the estimated DMD, predicted DMI and RFV. However, these improvements were accompanied by a reduced CP concentration and measurable cannabinoids, especially THC-related compounds and CBD, which remain central constraints for practical feed use. Because this study was limited to laboratory-based evaluation and did not include animal feeding or digestibility validation, the findings should be interpreted as comparative estimates of feed potential rather than direct evidence of livestock performance. Therefore, the practical use of hemp leaf-based feeds should be considered cautiously and only under appropriate cannabinoid monitoring, regulatory

compliance and animal-based validation.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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