

Effects of different additives on nutritional quality and fermentation characteristics of industrial hemp silage

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ABSTRACT. This study aimed to evaluate the effects of ground wheat grain, formic acid and a bacterial inoculant on fermentation quality, chemical composition and estimated feeding value of hemp silage. Industrial hemp (*Cannabis sativa* L.) was harvested at the full-flowering stage, chopped to 1–2 cm fragments and ensiled using four treatments: control (no additive), 5% ground wheat grain, 0.5 kg/t formic acid and 0.05 ml/kg bacterial inoculant, each prepared in triplicate. Fresh hemp showed high concentrations of neutral detergent fibre (79.46%), acid detergent fibre (65.48%) and acid detergent lignin (11.55%), together with low crude protein (3.41%) and water-soluble dry matter, indicating limited fermentability. Additives significantly influenced silage pH and Fleig scores ($P < 0.001$). Formic acid addition resulted in the most favourable fermentation profile, with the lowest pH (4.56) and highest Fleig score (92.64). Ground wheat increased water-soluble dry matter, Brix values, and crude protein content (4.88%) and improved silage quality. In contrast, bacterial inoculant caused only a minor decrease in pH, likely due to the low sugar content and high buffering capacity of hemp forage. Energy-related parameters, including total digestible nutrients, metabolizable energy and net energy fractions, were not significantly affected by additives, likely due to the fibrous and lignified structure of hemp. However, the improvement in relative feed value caused by wheat grain addition indicates that carbohydrate supplementation can partially improve feeding value of hemp silage. Overall, industrial hemp is a low-protein, high-fibre forage with limited fermentability, although formic acid and carbohydrate-based additives can improve its fermentation characteristics.

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Introduction

Industrial hemp (*Cannabis sativa* L.) is an annual herbaceous crop of the family *Cannabaceae*, traditionally cultivated for fibre, seeds and industrial applications. In current legislation, ‘industrial hemp’ refers to fibre-type cultivars with low tetrahydrocannabinol (THC) content (e.g. $\leq 0.2\%$ in the European Union) (EFSA FEEDAP, 2011). These cultivars still contain a complex phytochemical profile, including cannabinoids such as cannabidiol (CBD), as well as

terpenes and phenolic compounds; however, from a feed safety perspective, the primary concern is associated with potential residues of THC and other phytocannabinoids in edible animal products (EFSA FEEDAP, 2011; EFSA CONTAM, 2015; Irawan et al., 2025).

Interest in the use of hemp in animal nutrition has increased in recent years. Hemp seeds and its by-products (cake, hulls) are valued as sources of oil, protein and fibre for various livestock species (Mustafa et al., 1999; Klir et al., 2019; Bailoni et al., 2021).

Hemp seeds typically contain 25–35% oil and 20–25% crude protein (CP), with a high proportion of polyunsaturated fatty acids, whereas hemp seed cake may contain 30–35% CP and a favourable amino acid profile (Callaway, 2004; Bailoni et al., 2021). The whole plant, including stems and leaves, has been proposed as a potential forage source due to its high fibre content (Andre et al., 2016; Klir et al., 2019; Klevenhusen et al., 2024). Nevertheless, the presence of anti-nutritional factors such as phytic acid and tannins, together with concerns related to cannabinoid residues in milk and meat, has led to regulatory restrictions and the requirement for risk assessment (EFSA FEEDAP, 2011; EFSA CONTAM, 2015; Irawan et al., 2025).

The utilisation of industrial hemp as silage material has gained attention because of its rapid growth, high biomass yield and suitability for sustainable production systems. Under favourable conditions, hemp can produce up to 25 t of above-ground dry matter per hectare (Struik et al., 2000). The optimal harvest stage for ensiling is reported to be between early flowering and seed set, when soluble carbohydrate and protein concentrations are highest (Gürbüz et al., 2022). Although cellulose content remains relatively stable during maturation, lignification processes intensify after flowering, which limits fibre degradability (Klir et al., 2019; Struik et al., 2000). Moreover, the low content of natural water-soluble carbohydrates and high buffering capacity of hemp herbage may inhibit the growth of lactic acid bacteria, thereby hindering a rapid pH decline in the absence of additives (Gürbüz et al., 2022; Wróbel et al., 2023). Recent studies have suggested that homo- and heterofermentative lactic acid bacteria inoculants can markedly improve fermentation kinetics, aerobic stability and microbial composition of hemp silage (Wróbel et al., 2023; Shah et al., 2024).

Although previous research provides valuable information on the composition and functional properties of hemp and hemp-derived feedstuffs, data on the fermentation characteristics, chemical profile, energy values and fibre digestibility of whole-plant hemp silage remain limited. In particular, the effects of different additive strategies on fermentation profile and feeding value are not sufficiently explored.

To this end, the objective of the present study was to (i) determine the chemical composition and fermentation characteristics of industrial hemp silage prepared with several different additives, (ii) assess the effects of these additives on fibre fractions and nutritional indices, and (iii) evaluate the overall

feeding value of whole-plant hemp silage for ruminants. The findings provide data on the suitability of industrial hemp as a sustainable forage source and support the development of effective additive strategies in hemp silage production.

Material and methods

Study area and plant material

Industrial hemp (*Cannabis sativa* L.) was employed as the silage material. Plants used for ensiling were cultivated during the 2024 growing season at the experimental fields (40°19'41"N, 36°27'30"E) of the Middle Black Sea Transitional Zone Agricultural Research Institute (Tokat, Türkiye). All plants were randomly harvested from a single plot at the full flowering stage and manually chopped into 1–2 cm fragments.

Experimental design and silage preparation

Four silage treatments were prepared: control (C) – no additive; wheat (W) – 5% ground wheat grain (fresh weight basis); formic acid (FA) – 0.5 kg/t formic acid (Merck, CAS 64-18-6); bacterial inoculant (BI) – 0.05 ml/kg commercial inoculant.

Each treatment was prepared in triplicate (n = 3). The microbial composition of the inoculant is presented in Table 1.

Table 1. Composition of the bacterial inoculant

Microorganism	Amount, CFU/ml
<i>Pediococcus acidilactici</i> NCIMB 30005	2 × 10 ⁸
<i>Pediococcus pentosaceus</i> DSM 16244	1 × 10 ⁸
<i>Lactobacillus plantarum</i> DSM 29025	1 × 10 ⁸
<i>Lactobacillus buchneri</i> KKP/907/P	1 × 10 ⁸
<i>Lactobacillus casei</i> DSM 28872	1 × 10 ⁸

total microorganism count was 6 × 10⁸ CFU/ml; CFU – colony-forming unit

Approximately 500 g of fresh chopped hemp material was packed into polyethylene vacuum bags (35 × 25 cm, T.M.Q.G. vacuum bags, Türkiye), vacuum-sealed (Kumtel HVSE-01, Kayseri, Türkiye), and stored at 24 ± 2 °C in a dark, dry environment for 12 months. After opening, silages were first evaluated for fermentation quality indicators (pH, expected pH, Fleig score, water-soluble dry matter (WSDM) and Brix). Representative subsamples (5 g) were then taken for dry matter (DM) determination, and DM content was measured by oven-drying at 105 ± 1 °C to constant weight. The remaining silage material was subsequently dried at 105 ± 1 °C, ground to pass through a 1 mm sieve, and stored for chemical analyses.

pH and water-soluble dry matter analyses

Silage pH was determined by homogenising 25 g of sample with 250 ml of distilled water, shaking for 3 min, and measuring pH using an Orion Lab Star PH111 pH meter (Thermo Scientific, USA). The expected pH was calculated according to Meeske (2005). Silage quality was evaluated using the Fleig Score (DLG, 1997).

WSDM was measured by extracting 20 g of silage with 200 ml of distilled water for 30 min, followed by filtration and oven-drying the filtrate at 105 °C (Memmert UN110, Germany) to constant weight. Soluble solids were additionally quantified using an HI 96801 digital refractometer (Hanna Instruments, USA) and expressed as %Brix.

Chemical analyses

Dried samples were ground in an IKAA10 laboratory mill (IKA-Werke, Germany) and passed through a 1 mm sieve prior to analysis. Chemical composition was determined according to the methods of AOAC (1990) and Van Soest et al. (1991). The following parameters were assessed: CP, ether extract (EE), crude ash (CA), acid detergent fibre (ADF), neutral detergent fibre (NDF) and acid detergent lignin (ADL).

CP was measured using the Kjeldahl method with a UDK 139 distillation unit (Velp, Italy). CA was assayed by combustion at 550 °C in a Heraeus MR 170 muffle furnace (Germany), and organic matter (OM) was calculated as $100 - CA$ in accordance with the AOAC (1990) protocol. EE was determined using a Gerhardt Soxtherm 416 system (Germany) with n-hexane as the extraction solvent. NDF and ADF were analysed using a FIWE-3 fibre analyser (Velp, Italy) according to the detergent system of Van Soest et al. (1991). ADL was determined separately by treating the ADF residue with 72% sulphuric acid, also following the protocol of Van Soest et al. (1991).

Calculation of cellulose and haemicellulose

Cellulose and haemicellulose contents were not measured directly but were calculated based on fibre fractionation data according to Van Soest et al. (1991) as follows: cellulose (% DM) = ADF – ADL, haemicellulose (% DM) = NDF – ADF.

These indices were used to characterise structural carbohydrate composition and to support the evaluation of fibre degradability and feeding value.

Energy values

Digestibility- and energy-related nutritional parameters were calculated from the chemical composition data using predictive procedures described by

Weiss (1994), Jeranyama and Garcia (2004), Güney et al. (2016) and the Nutrient Requirements of Dairy Cattle (NRC, 2001). The evaluated parameters included non-fibre carbohydrates (NFC), nitrogen-corrected neutral detergent fibre (NDFn), NDF digestibility (NDFd), digestible dry matter (DDM), dry matter intake as a percentage of body weight (DMI), total digestible nutrients (TDN), relative feed value (RFV), as well as the energy fractions: digestible energy (DE), metabolizable energy (ME), net energy for lactation (NEL), net energy for maintenance (NEM), and net energy gain (NEG). NDFd was estimated using predictive equations rather than an *in vitro* digestion assay.

Cannabinoid analyses

THC, CBD, and cannabinol (CBN) contents were determined according to the UNODC (2009) guidelines using gas chromatography with flame ionisation detection (GC-FID; Perkin Elmer Clarus 580). All cannabinoid analyses were conducted by the Black Sea Agricultural Research Institute (Karadeniz Tarımsal Araştırma Enstitüsü, Samsun, Türkiye).

Statistical analysis

Data were analysed using a one-way ANOVA model. Results are presented as mean plus standard error (SE). Differences between groups were assessed using Tukey's test, with $P < 0.05$ considered statistically significant. All analyses were performed using SPSS 25.

Results and discussion

Chemical composition and feeding value of fresh hemp herbage

The chemical composition and feeding value parameters of pre-ensiled whole-plant hemp are presented in Tables 2A and B. DM content was 37.25%, CA 5.15% and OM 94.85%. EE (1.50% DM) and CP (3.41% DM) contents were low, whereas NDF (79.46% DM), ADF (65.48% DM) and ADL (11.55% DM) levels were high. This profile indicates that industrial hemp herbage is a fibre-rich, protein-poor forage whose digestibility is limited by lignification. Hemicellulose and cellulose contents, calculated according to Van Soest fibre fractionation procedures (Van Soest et al., 1991), were 13.97% and 53.94% DM, respectively, NDFn was 73.89%, and NDFd was 89.10%.

The NFC content (16.05% DM) (Table 2B) indicates that soluble carbohydrates in hemp herbage

Table 2A. Chemical composition and fibre fractions of fresh industrial hemp

DM	CA	OM	EE	CP	NDF	ADF	ADL	CEL	HCEL	THC	CBD	CBN
37.25	5.15	94.85	1.50	3.41	79.46	65.48	11.55	53.94	13.97	0.0019	0.1039	n.d.

DM – dry matter (% fresh matter), CA – crude ash (% DM), OM – organic matter (% DM), EE – ether extract (% DM), CP: crude protein (% DM), ADF – acid detergent fibre (% DM), NDF – neutral detergent fibre (% DM), ADL – acid detergent lignin (% DM), CEL – cellulose (% DM), HCEL – haemicellulose (% DM), THC – Δ^9 -tetrahydrocannabinol (% DM), CBD – cannabidiol (% DM), CBN – cannabinol (% DM), n.d. – not detected. All components are expressed on a DM basis unless otherwise stated

Table 2B. Energy, digestibility and feed value

NDFn	NDFd	NFC	TDN	DDM	DMI	RFV	DE	ME	NEL	NEM	NEG
73.89	89.10	16.05	81.01	37.89	1.51	44.36	14.94	13.20	7.80	9.03	6.20

NDFn – nitrogen-corrected neutral detergent fibre (% DM), DM – dry matter, NDFd – neutral detergent fibre digestibility (% of NDF), NFC – non-fibre carbohydrates (% DM), TDN – total digestible nutrients (% DM), DDM – digestible DM (% DM), DMI – dry matter intake (% of body weight), RFV – relative feed value (index), DE – digestible energy (MJ/kg DM), ME – metabolizable energy (MJ/kg DM), NEL – net energy for lactation (MJ/kg DM), NEM – net energy for maintenance (MJ/kg DM), NEG – net energy for gain (MJ/kg DM). All values are expressed on a DM basis unless otherwise stated; DMI is expressed as % of body weight and RFV as an index

are rather low, which is consistent with recent studies reporting that hemp herbage and silage are characterised by high structural carbohydrate fractions and relatively low concentrations of rapidly fermentable carbohydrates (Bailoni et al., 2021; Wróbel et al., 2023; Shah et al., 2024). TDN and DDM were 81.01 and 37.89%, respectively, while DMI was estimated at 1.51% body weight (Table 2B) using established empirical equations (Rohweder et al., 1978; Jeranyama and Garcia, 2004; Güney et al., 2016). Consequently, the RFV was 44.36, indicating low-to-moderate forage quality and placing fresh hemp herbage within the range generally classified as medium-quality roughage (Rohweder et al., 1978; Güney et al., 2016).

Energy values were calculated as follows: MJ/kg DM: DE 14.94, ME 13.20, NEL 7.80, NEM 9.03 and NEG 6.20 (Table 2B), based on standard equations for ruminant feeds (Weiss, 1994; Jeranyama and Garcia, 2004). These results suggest that, despite its high fibre content, hemp herbage should be considered a moderate energy source for ruminants. This is in line with previous reports showing that hemp forages and hemp-derived co-products can supply ME values comparable to other medium-quality roughages or protein supplements, although their protein contribution varies widely depending on plant part and processing (Mustafa et al., 1999; Bailoni et al., 2021; Shah et al., 2024).

The cannabinoid profile showed a very low THC (0.0019%), higher CBD (0.1039%) and non-detectable CBN concentrations (Table 2A). From a feed safety perspective, these values are well below the levels of concern discussed in regulatory and risk-assessment documents for hemp in animal nutrition (EFSA FEEDAP, 2011; EFSA CONTAM, 2015; Muedi et al., 2024; Irawan et al., 2025).

Overall, the present findings confirm that whole-plant industrial hemp harvested at the stage used in this study represents a lignified, fibre-rich forage with limited protein supply and moderate energy density, consistent with previous descriptions of hemp as a roughage source in ruminant diets (Klir et al., 2019; Bailoni et al., 2021; Gürbüz et al., 2022).

Effects of additives on fermentation characteristics

The influence of the additives on the chemical composition, fermentation characteristics and calculated feeding values of the silages are summarised in Table 3. Silage DM ranged from 33.44 to 36.99%, with the highest value observed in the W treatment and the lowest in the BI group; however, these differences were not statistically significant ($P = 0.076$). The DM range obtained in the present study was consistent with values previously reported for hemp silages produced under laboratory-scale ensiling conditions (Wróbel et al., 2023; Klevenhusen et al., 2024).

In contrast, silage pH, a key indicator of fermentation quality, differed markedly between treatments ($P < 0.001$). The lowest pH was observed in the FA group (4.56), followed by the W group (4.89). The control (5.55) and BI (5.51) treatments had higher pH values, indicating less extensive acidification (Table 3). The rapid pH decline induced by formic acid, which suppresses undesirable microorganisms through a ‘starter acidification’ effect, is well documented in grass and legume silages (Kung and Shaver, 2001; Meeske, 2005) and has been clearly confirmed in the present hemp silages. Similar improvements in fermentation profile and reduction in pH with organic acids were reported for other difficult-to-ensile crops, including high-buffering or low-sugar forages (Kung and Shaver, 2001).

Table 3. Effects of different additives on chemical and fermentation characteristics of hemp silage (n = 3)

Indices	Additive				P-value
	C	W	FA	BI	
DM	36.05 ± 1.30	36.99 ± 0.24	34.95 ± 0.85	33.44 ± 0.56	0.076
CA	5.08 ± 0.02	5.18 ± 0.32	5.05 ± 0.17	5.39 ± 0.34	0.768
OM	94.92 ± 0.02	94.82 ± 0.32	94.95 ± 0.17	94.61 ± 0.34	0.768
EE	1.45 ± 0.12 ^a	2.15 ± 0.11 ^b	1.24 ± 0.05 ^a	1.50 ± 0.09 ^a	0.001
CP	3.54 ± 0.07 ^b	4.88 ± 0.04 ^a	2.23 ± 0.04 ^d	3.02 ± 0.11 ^c	<0.001
pH	5.55 ± 0.01 ^a	4.89 ± 0.07 ^b	4.56 ± 0.03 ^c	5.51 ± 0.02 ^a	<0.001
Expected pH	4.74 ± 0.05 ^{ab}	4.77 ± 0.01 ^a	4.70 ± 0.03 ^{ab}	4.64 ± 0.02 ^b	0.036
Fleig score	54.98 ± 2.37 ^b	83.37 ± 2.98 ^a	92.64 ± 1.99 ^a	51.34 ± 1.79 ^b	<0.001
WSDM	0.38 ± 0.01 ^{ab}	0.44 ± 0.03 ^a	0.37 ± 0.01 ^{ab}	0.31 ± 0.02 ^b	0.015
Brix	0.27 ± 0.03 ^b	0.47 ± 0.03 ^a	0.47 ± 0.13 ^{ab}	0.57 ± 0.03 ^a	0.019
NDF	76.66 ± 0.78	64.76 ± 2.66	76.52 ± 1.53	68.07 ± 8.84	0.254
ADF	70.44 ± 0.70	53.44 ± 1.70	63.72 ± 2.50	57.52 ± 8.39	0.112
ADL	13.44 ± 1.48	14.07 ± 1.65	15.16 ± 0.36	16.53 ± 2.16	0.549
CEL	56.99 ± 0.88	39.37 ± 3.34	48.56 ± 2.14	40.99 ± 10.53	0.186
HCEL	6.22 ± 0.42	11.32 ± 1.74	12.80 ± 3.33	10.54 ± 2.93	0.313
NDFn	71.29 ± 0.72	60.22 ± 2.47	71.16 ± 1.43	63.30 ± 8.22	0.254
NDFd	86.88 ± 1.34	83.55 ± 2.42	85.12 ± 0.52	80.33 ± 5.61	0.535
NFC	18.64 ± 0.61	27.56 ± 2.75	20.32 ± 1.46	26.78 ± 8.33	0.433
TDN	79.63 ± 1.13	79.66 ± 1.03	78.28 ± 0.16	77.11 ± 1.76	0.404
DDM	34.03 ± 0.55	47.27 ± 1.33	39.26 ± 1.94	44.09 ± 6.54	0.112
DMI	1.57 ± 0.02	1.86 ± 0.08	1.57 ± 0.03	1.83 ± 0.27	0.348
RFV	41.32 ± 1.05	68.27 ± 4.61	47.74 ± 2.26	65.27 ± 19.44	0.242
DE	14.69 ± 0.21	14.69 ± 0.19	14.44 ± 0.03	14.22 ± 0.32	0.400
ME	12.94 ± 0.21	12.95 ± 0.19	12.69 ± 0.03	12.47 ± 0.33	0.403
NEL	7.66 ± 0.12	7.66 ± 0.10	7.52 ± 0.02	7.40 ± 0.18	0.403
NEM	8.82 ± 0.17	8.82 ± 0.16	8.62 ± 0.03	8.43 ± 0.27	0.409
NEG	6.02 ± 0.15	6.02 ± 0.13	5.85 ± 0.02	5.69 ± 0.23	0.397

C – control, W – ground wheat grain, FA – formic acid, BI – bacterial inoculant, DM – dry matter (% fresh matter), CA – crude ash (% DM), OM – organic matter (% DM), EE – ether extract (% DM), CP – crude protein (% DM), pH – silage pH (unitless), Expected pH – calculated according to Meeske (2005), Fleig score – silage quality index, WSDM – water-soluble dry matter (% w/v), Brix – soluble solids (%), NDF – neutral detergent fibre (% DM), ADF – acid detergent fibre (% DM), ADL – acid detergent lignin (% DM), CEL – cellulose (% DM), HCEL – hemicellulose (% DM), NDFn – nitrogen-corrected NDF (% DM), NDFd – neutral detergent fibre digestibility (% of NDF), NFC – non-fibre carbohydrates (% DM), TDN – total digestible nutrients (% DM), DDM – digestible dry matter (% DM), DMI – dry matter intake (% of body weight), RFV – relative feed value (index), DE – digestible energy (MJ/kg DM), ME – metabolizable energy (MJ/kg DM), NEL – net energy for lactation (MJ/kg DM), NEM – net energy for maintenance (MJ/kg DM), NEG – net energy for gain (MJ/kg DM); values are presented as mean ± standard error (n = 3); ^{a-d} means within a row with different superscripts are significantly different at $P < 0.05$; values are expressed on a DM basis unless otherwise stated

‘Expected pH’ values, calculated using the equation of Meeske (2005), also differed between treatments ($P = 0.036$), although the absolute range (4.64–4.77) was small and of limited practical relevance (Table 3). Nevertheless, Fleig scores clearly differentiated the treatments ($P < 0.001$), as silages treated with formic acid (92.64) and wheat (83.37) were classified as good to very good quality, whereas the C (54.98) and BI (51.34) silages were of medium quality according to DLG and national recommendations (DLG, 1997). These results underline the need to incorporate additives in low-sugar forages such as hemp, and are consistent with pilot studies demonstrating that the fermentation quality of hemp silages is highly dependent on both ensiling conditions and the use of appropriate additives (Wróbel et al., 2023; Klevenhusen et al., 2024).

WSDM differed significantly between groups ($P = 0.015$), with the highest values obtained in the W group (0.44% w/v), and the lowest in the BI group (0.31% w/v) (Table 3). Wheat addition increased the initial supply of soluble carbohydrates, providing a more favourable substrate for lactic acid bacteria, which was reflected in higher WSDM and Brix values. Refractometric Brix measurements also differed among treatments ($P = 0.019$), with higher values in the wheat and BI groups than in the control. Similar responses to cereal grain or by-product supplementation have been reported for other low-sugar forages, where starch and simple sugars improved lactic fermentation and reduced the risk of clostridial activity (Kung and Shaver, 2001). However, the relatively high pH in BI demonstrated that the inoculant alone was insufficient to optimise

fermentation under conditions of low water-soluble carbohydrates and high buffering capacity. This observation supports studies showing that lactic acid bacteria inoculants have limited effectiveness in low-sugar forages unless combined with sugar supplementation or other supportive measures (Kung and Shaver, 2001; Filya, 2003).

Chemical composition, fibre fractions and feeding value of hemp silages

CA and OM contents were not significantly affected by additives ($P > 0.05$), indicating that mineral concentration remained largely unchanged during fermentation (Table 3). Ether extract, however, was influenced by treatments ($P = 0.001$), with the highest value recorded in the W group (2.15% DM). This increase likely reflected both the intrinsic fat content of wheat and the higher overall DM content. The other treatments showed lower and similar ether extract levels (1.24–1.50% DM), consistent with the low-fat content of hemp forage and hemp-based roughages reported in the literature (Shah et al., 2024).

CP content (Table 3) was significantly affected by additives ($P < 0.001$). The highest CP was observed in the wheat group (4.88% DM); the control (3.54% DM) and BI (3.02% DM) treatments showed intermediate values, and the FA group had the lowest CP content (2.23% DM). The increase in CP in the W group can be explained by both the protein content of wheat itself and a concentration effect associated with higher DM content. Similar modest improvements in CP concentration have been reported when cereal grains or protein-rich co-products were ensiled with structurally rich forages (Bailoni et al., 2021). The lower CP value in the FA group may be related to the effect of formic acid on protein solubility and nitrogen fractions, as strong acidification can alter the distribution of true protein and non-protein nitrogen (Kung and Shaver, 2001; Meeske, 2005).

No statistically significant differences among treatments were detected for fibre fractions, including NDF, ADF, ADL, cellulose, and haemicellulose ($P > 0.05$) (Table 3). Nevertheless, numerically lower NDF and ADF values, along with slightly higher hemicellulose contents, were observed in the W and BI groups. The consistently high ADL content (13–16% DM) in all treatments appear to be the main factor limiting the feeding value of hemp silages, which confirms reports on the negative impact of lignification on forage digestibility (Van Soest et al., 1991; Klir et al., 2019). Similar high

ADL levels have been recorded in hemp stubble, hay and other hemp roughages, and are considered a key obstacle for their use as the sole forage source in high-producing ruminants (Zicarelli et al., 2025).

Similarly, NDFn, NDF digestibility, NFC, TDN, DDM, DMI and RFV did not differ significantly between treatments ($P > 0.05$) (Table 3). However, numerically higher RFV values in the W (68.27) and BI (65.27) groups compared with the control (41.32) and FA (47.74) groups suggested a limited but favourable effect of these additives on forage quality. Overall, RFV values in the range of 40–70 indicate that hemp silage can be classified as a medium-quality roughage, consistent with results reported for hemp-based forages and co-products used in ruminant diets (Mustafa et al., 1999; Klir et al., 2019; Bailoni et al., 2021; Shah et al., 2024). From a practical standpoint, these findings support the inclusion of hemp silage in ruminant rations as a complementary roughage source, provided that it is balanced with higher-protein and higher-quality forages or concentrates.

Energy fractions

Energy-related parameters (DE, ME, NEL, NEM, NEG) were not affected by the additives ($P > 0.05$) and showed only minor variation among treatments (MJ/kg DM: DE: 14.22–14.69, ME: 12.47–12.95, NEL: 7.40–7.66, NEM: 8.43–8.82, NEG: 5.69–6.02) (Table 3). This indicates that the additives did not substantially alter the gross energy content of hemp silage, and their effects were observed primarily in fermentation quality and, to a lesser extent, in protein and fat fractions. The ME values obtained in the current study are comparable to those reported for hemp forage and by-products used as partial replacements for conventional forages such as alfalfa or grass hay (Shah et al., 2024), as well as for hemp meal or hempseed co-products used as protein supplements (Mustafa et al., 1999; Bailoni et al., 2021).

Overall, the present findings suggest that hemp silage can serve as a moderate energy source in ruminant diets, but requires supplementation with additional protein and, in high-production systems, with higher-quality forages or concentrates. This conclusion is consistent with recent reviews emphasising that hemp and hemp by-products are most suitable as complementary components of ruminant diets, supplying fibre, bioactive compounds, and moderate amounts of energy rather than serving as the only forage source (Bailoni et al., 2021; Muedi et al., 2024; Irawan et al., 2025).

A limitation of the present study is that ensiling was conducted in laboratory-scale vacuum bags and that a comprehensive fermentation profile was not determined. Specifically, fermentation metabolites (lactic, acetic and butyric acids) and microbial populations (lactic acid bacteria, yeasts and moulds) were not quantified. In addition, NDF digestibility was estimated using predictive equations rather than *in vitro* methods. Future studies should evaluate hemp silage under farm-scale conditions and include detailed organic acid profiling, microbiological analyses, aerobic stability tests, and *in vitro/in vivo* feeding trials to better characterise fermentation pathways and feeding value.

Conclusions

This study evaluated the effects of wheat, formic acid and a bacterial inoculant on the fermentation parameters, chemical composition, and calculated feeding value of silages prepared from whole-plant industrial hemp (*Cannabis sativa* L.). Pre-ensiled hemp herbage was characterised by high neutral detergent fibre, acid detergent fibre, and acid detergent lignin contents, together with low crude protein and soluble carbohydrate levels, confirming that industrial hemp is a fibre-rich forage with low protein value and digestibility.

Among the tested additives, formic acid was the most effective in improving fermentation quality, producing the lowest pH, the highest Fleig score, and silages of good to very good quality. Wheat supplementation increased water-soluble carbohydrate and crude protein concentrations, raised water-soluble dry matter and Brix values, and led to a modest increase in relative feed value. In contrast, under conditions of low water-soluble carbohydrate content and high buffering capacity, the bacterial inoculant alone exerted a limited effect on pH reduction and overall silage quality.

Energy-related parameters (digestible energy, metabolizable energy, net energy for lactation, net energy for maintenance, and net energy for gain) were not significantly affected by the additives, and thus, hemp silage constituted a moderate energy source in all treatments. Overall, the findings indicate that industrial hemp silage should primarily be regarded as a structural fibre source in ruminant diets, and that its low protein content, as well as modest energy value, requires supplementation with additional feedstuffs.

In conclusion, the use of organic acids and/or carbohydrate sources appears necessary to obtain acceptable fermentation quality in hemp silages.

Future research should focus on *in vitro* and *in vivo* digestibility of hemp silage, the effects of different additives on rumen fermentation kinetics and microbial ecology, and the potential transfer and accumulation of cannabinoids in edible animal products.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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