Iranian Society of Animal Science

Journal of Livestock Science and Technologies

Shahid Bahonar University of Kerman

ISSN: 2322-3553 (Print) ISSN: 2322-374X (Online)

Paper type: Original Research

Chemical composition, fermentation characteristics and digestibility of potato haulm silage from six localities in Kerman province, Iran

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Received: 28 Jun 2026,
Received in revised form: 28 Jul 2026,
Accepted: 03 Aug 2026,
Published online: 05 Aug 2026,

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Abstract This study evaluated the chemical composition, glycoalkaloids (GA) content, fermentation quality and *in vitro* digestibility of fresh and ensiled potato haulms (PoH) collected from six agro-climatically diverse locations within Kerman province (Jiroft, Anbarabad, Rudbar, Kahnuj, Faryab, and Manujan). Representative samples were collected from a single commercial field per location, chopped to 3-5 cm, vacuum-sealed in polyethylene silo bags (5 kg), and ensiled for 45 days. The experiment was conducted in a completely randomized design with six treatments (locations) and five replications, and data were analyzed using the GLM procedure of SAS. Location had a large effect on crude protein (CP; P<0.001), acid detergent fiber (ADF; P=0.005), water-soluble carbohydrates (WSC; P=0.05), ash (P<0.01), and GA concentrations (P=0.003) in fresh PoH, with CP varying from 17.8% to 24.0% and GA from 678 to 968 mg/kg dry matter (DM) between locations. During ensiling WSC decreased by 71% (8.20% to 2.38%; P<0.01), nitrate concentration decreased by 58% (0.703% to 0.294%; P<0.01) and total GA content decreased by 43.7% (808 to 455 mg/kg DM; P<0.01) which is the result of acidic hydrolysis and microbial degradation during fermentation. Silage fermentation was characterized by consistently high lactic acid concentrations (63.7-69.2 g/kg DM) and negligible butyric acid (<0.25 g/kg DM) across all locations, indicative of well-preserved, clostridium-free silages. DM digestibility (DMD) decreased from 60.8% to 56.6% and metabolizable energy (ME) from 2.14 to 2.00 Mcal/kg DM (P<0.01) after ensiling. The results suggest that ensiling substantially reduced antinutritional factors while maintaining the overall feeding potential of PoH, although modest reductions in DMD and ME were observed. Thus, the use of potato haulm silage as a suitable ruminant feed in semi-arid areas of Iran is recommended.

Keywords: ensiling, glycoalkaloids, *in vitro* digestibility, nitrate, potato plant

Introduction

Potato (*Solanum tuberosum* L.) is one of the most economically significant food crops worldwide, ranking as the fourth largest staple crop after wheat, rice, and maize (FAO, 2023). According to the Food and Agriculture Organization of the United Nations, global potato production reached approximately 375 million tons in 2022, with Iran ranking as the fourth largest potato producer in Asia, after China, India, and Bangladesh (FAO, 2023). In Iran about 5 million tons of potato are produced annually from about 164000 hectares (Dadrasi et al., 2022), producing substantial quantities of above-ground vegetative biomass known as potato haulm (PoH), which includes stems, leaves, and vines left in the field after tuber harvest (Kaplan et al., 2018). Despite this substantial yield, PoH is commonly eliminated through incineration or soil incorporation, practices that result in greenhouse gas emissions, soil microbiome disruption, and significant loss of organic matter (OM; Dubey et al., 2019; Venkatramanan et al., 2021). Given the escalating global demand for cost-effective and sustainable ruminant feed, particularly in semi-arid and arid agricultural regions where conventional forage resources are scarce, the valorization of PoH as animal feed warrants thorough scientific evaluation (Makkar, 2018; Hosseinabadi et al., 2026). The nutritional composition of PoH has been examined in a limited number of published studies. Kaplan et al. (2018) evaluated the PoH of five commercially grown potato cultivars (Milva, Laura, Granola, Europrima, and Jelly) in Turkey and reported crude protein (CP) concentrations ranging from 10.85 to 14.48%, ash from 5.22 to 9.10%, neutral detergent fiber (NDF) from 47.99 to 60.91% and acid detergent fiber (ADF) from 22.46 to 33.94% on a DM basis. The metabolizable energy (ME) values of PoH were estimated between 1.78 and 2.22 Mcal/kg DM, with OM digestibility (OMD) ranging from 50.77% to 63.69%. These findings collectively indicated that PoH possesses a nutritive profile comparable or superior to many conventional roughages (Kilama et al., 2024).

The utilization of potato by-products in ruminant nutrition has been the subject of several feeding trials. Sadri et al. (2018) evaluated the effects of adding potato-wheat straw silage (PWSS) at levels of 0, 100, 200, or 300 g/kg DM in the diets of Mehraban fattening lambs. Their results demonstrated that PWSS inclusion up to 300 g/kg DM had no adverse effects on DM intake, growth performance, or blood metabolites, and actually improved feed efficiency and microbial nitrogen supply linearly with increasing PWSS inclusion, suggesting enhanced rumen function. More recently, Deng et al. (2023) evaluated the partial and complete replacement of whole-plant corn silage with potato vine and leaf mixed silage (PVS) in the diet of fattening Angus bulls. They demonstrated that PVS inclusion at 50% and 75% levels significantly elevated dietary CP content and digestibility, and increased blood urea nitrogen concentration compared to corn silage, although average daily gain and feed conversion ratio were adversely affected at both inclusion levels.

However, PoH contains glycoalkaloids (GAs), primarily α-solanine and α-chaconine (Baur et al., 2021), which are toxic to both humans and animals due to their anticholinesterase activity and membrane-disrupting capacity (Omayio et al., 2016), with acute toxicity in ruminants expected at oral doses above 40 mg/kg body weight (Schrenk et al., 2020). Nevertheless, ruminants exhibit greater resistance to GAs than monogastric species owing to the hydrolytic capacity of rumen microbiota, and ensiling may further reduce GA concentrations through microbial fermentation and acidic hydrolysis, thereby enhancing the safety and palatability of PoH as a feed resource (Malecky et al., 2017; Loh et al., 2020).

Despite the widespread global cultivation of potatoes, no comprehensive study has been reported to investigate the nutritional value of PoH in Iran, especially Kerman province. We hypothesized that 1) agro-environmental conditions across Kerman Province significantly affect the chemical composition and fermentation quality of PoH, and 2) ensiling would reduce glycoalkaloid concentrations while preserving nutritional value, making it a viable ruminant feed in arid regions. Therefore, the present study was designed to evaluate the chemical composition, *in vitro* digestibility, and fermentation quality of PoH from six regions in Kerman Province, Iran.

Materials and methods

Sample collection and silage preparation

Fresh PoH of *Sante* cultivar were collected immediately following commercial tuber harvest from six potato-producing locations in south Kerman Province (Jiroft, Anbarabad, Rudbar, Kahnuj, Faryab, and Manujan). Sampling was conducted over six consecutive days, with one location sampled each day. Each location represented one experimental treatment (n=6 treatments). The sampling sites represent diverse agro-climatic conditions across the province, ranging from tropical-influenced lowlands (Jiroft, Anbarabad) to semi-arid highlands (Rudbar, Kahnuj, Faryab, Manujan). At each location, a representative PoH sample was randomly harvested from a single commercial field, thoroughly mixed, and chopped to 3-5 cm particle size. The composite sample was then divided into five equal portions, each packed independently into a laboratory-scale polyethylene silo bag (5 kg capacity) to serve as experimental replicates (5 replicates per treatment), which were then vacuumed to remove excess air before sealing. The silages were stored for 45 days, after which representative samples were taken from each silo and then frozen at -20°C until analysis.

Chemical analysis

The DM content of fresh and ensiled PoH samples was determined by oven-drying at 60°C for 72 h. Then, CP (method 988.05), ash (method 904.05), ether extract (EE; method 920.39) concentrations were analyzed according to AOAC (2012) procedures. The NDF and ADF were determined sequentially by an Ankom200 fiber analyzer (Ankom Technology, Macedon, NY, USA) according to Van Soest et al. (1991). Water-soluble carbohydrates (WSC) and nitrate were determined using the anthrone (MAFF, 1982) and colorimetry methods (Singh, 1988), respectively. Concentration of oxalic acid was determined spectrophotometrically following the extraction of total oxalate from 1 g of sample using 50 mL of HCl (2 M) in a water bath at 80°C for 15 min (Savage et al., 2000). Concentrations of the major potato GAs, α-solanine and α-chaconine, were determined in freeze-dried and ground (1 mm) pre- and post-ensiled PoH samples using high-performance liquid chromatography with diode array detection (HPLC-DAD), according to the method presented by Friedman and Dao (1992).

Silage fermentation characteristics

After 45 days of ensiling, silo bags were opened and representative silage samples were collected for fermentation analysis. The silage pH was measured (Faithfull, 2002) immediately by a portable digital pH meter (Sartorius PT-10; Sartorius AG, Göttingen, Germany) in a distilled water extract (1:5, w/v). To determine ammonia-N, 9 mL of the silage extract were obtained by squeezing, mixed with 1 mL of a 7.2 N H_2SO_4, and analyzed using the phenol-hypochlorite assay (Galyean, 1997).

Two mL of the silage juice were pipetted into a micro-centrifuge tube with 0.5 mL of an acid solution (containing 20% orthophosphoric acid and 20 mM 2-ethyl butyric acid, as the internal standard), then centrifuged at 15000 × g for 15 min at 4°C. The supernatant was used to quantify the volatile fatty acids (VFA) using a gas chromatograph (UNICAM 4600; SB Analytical, Cambridge, UK) equipped with a flame ionization detector (250°C), split-injection port (1.0 µL injection), and a capillary column (Agilent J&W HP-FFAP, 10 m by 0.535 mm by 1.00 µm, 19095F-121; Agilent, Santa Clara, CA). The carrier gas was helium (column head pressure of 68.94 kPa), and the working temperatures of the injector and detector were 250 and 300°C, respectively. The initial column temperature was set at 80°C for 1 min and then increased by 20°C/min to 120°C followed by 6.2°C/ min to 140°C and thereafter by 20°C/min to 205°C.

In vitro digestibility

In vitro DM digestibility (DMD), OMD, digestible OM in the DM (DOMD), and ME were determined by the two-stage procedure of Tilley and Terry (1963) using ruminal microorganisms plus HCl/pepsin. Ruminal fluid was collected before the morning feeding from three fistulated Shal breed sheep, strained through four layers of cheesecloth, mixed with pre-warmed (39°C) McDougall's buffer at 1:4 ratio (v/v) under continuous CO-flushing to obtain the inoculum. Then, 500 mg of dried and ground (1 mm) sample were incubated in 40 mL of the inoculum in 100 mL sealed bottles at 39°C for 48 h in a shaking water bath. At the end of the incubation, the bottles were centrifuged for 15 min at 2000 × g to remove the liquid. The residues were treated with acid-pepsin solution for 48 h to simulate post-ruminal digestion. After the completion of the digestion, samples were filtered using a Buchner funnel and ashless filter paper. The filter papers containing the samples were oven-dried at 105°C, weighed, then burned in a furnace at 550°C and reweighed. Finally, DMD and OMD were calculated. The DOMD was calculated as OMD × % OM. ME (MJ/kg DM) of the PoH and their silages was estimated as 0.0157 × DOMD and 0.0160 × DOMD, respectively (AFRC, 1993). The DMD and OMD values were divided by 4.18 for conversion to Mcal/kg DM.

Statistical analysis

Data were checked for normal distribution by the PROC Univariate and analyzed using the PROC GLM of SAS (2013) in a completely randomized design. Mean comparison was performed using the Duncan's multiple range test. Differences between pre- and post-ensiled samples were examined using a t- test. Statistical significance was set at $P \leq 0.05$, and trends were declared if $P > 0.05$ and $P < 0.10$). The following statistical model was used to analyze the data:

$Y_{ij} = \mu + T_i + e_{ij}$

In the above model, Y_{ij}: observed value, μ: mean, T_i: treatment effect, and e_{ij}: experimental error.

Results

Chemical composition of fresh PoH

The chemical composition of fresh PoH differed across the six sampling locations (Table 1). Crude protein concentration was 17.8 to 24.0% DM ($P < 0.05$), and ash content was 16.45 to 21.35% DM ($P = 0.01$). The ADF, WSC, and GA concentration also differed among locations. However, DM, NDF, nitrate, and oxalic acid concentrations were similar across locations. The Anbarabad had the highest CP (24.0% DM) and glycoalkaloid (968 mg/kg DM) concentrations among the evaluated regions. The lowest concentration of GA (678 mg/kg DM) was found in Faryab. The concentration of WSC ranged from 7.06 to 9.05 % DM across locations.

Effect of ensiling on chemical composition

Ensiling induced significant changes in the chemical composition of PoH (Table 1). Overall DM content increased from 20.4% to 22.3%. CP content decreased from 20.4% to 19.9%. EE and ADF contents were not significantly affected by ensiling. Ash content increased significantly from 19.3% to 21.6% following ensiling. The NDF content showed a numerical increase from 37.5% to 39.4%. The WSC and nitrate contents decreased by 70% and 58%, respectively. Oxalic acid content was not significantly affected by ensiling. Total GA content was significantly reduced by ensiling, declining from 808 mg/kg DM to 455 mg/kg DM, a 43.7% relative reduction.

Silage fermentation characteristics

The fermentation characteristics of PoH silages are shown in Table 2. The silage pH ranged from 3.71 (Anbarabad) to 4.77 (Rudbar), with a mean of 4.36, and did not differ significantly among locations. Ammonia nitrogen (NH_3N) content, expressed as g/kg of total nitrogen, varied significantly among locations, ranging from 45.9 (Faryab) to 54.3 (Kahnuj). Lactic acid concentrations ranged from 63.7 g/kg DM (Manujan) to 69.2 g/kg DM (Anbarabad) and did not differ significantly among locations. Acetic acid concentrations were moderate and relatively uniform across locations, ranging from 16.9 to 17.8 g/kg DM (P=0.62). Propionic and butyric acid concentrations were extremely low across all locations (<0.5 g/kg DM) across all locations (P>0.05).

Table 1. Chemical composition (% or as stated) of potato haulms pre- and post-ensiling

	DM	CP	EE	Ash	NDF	ADF	WSC	Nitrate	Oxalic acid	Glycoalkaloids (mg/kg DM)
Pre-ensiling										
Jiroft	20.3	21.1^{b}	3.05^{b}	16.45^{c}	35.8	13.0^{b}	8.97^{a}	0.683	0.394	842^{b}
Anbarabad	21.0	24.0^{a}	3.43^{a}	19.9^{ab}	40.2	17.0^{a}	8.54^{ab}	0.710	0.389	968^{a}
Rudbar	21.5	19.4^{c}	3.55^{a}	20.6^{a}	38.8	17.9^{a}	7.30^{bc}	0.694	0.431	715^{c}
Kahnuj	19.8	22.1^{b}	3.40^{a}	21.35^{a}	37.6	17.4^{a}	9.05^{a}	0.701	0.418	891^{b}
Faryab	18.9	18.2^{d}	3.24^{ab}	18.05^{bc}	36.8	16.7^{a}	8.29^{bc}	0.737	0.389	678^{c}
Manujan	20.7	17.8^{d}	3.49^{a}	19.65^{ab}	35.9	16.8^{a}	7.06^{c}	0.696	0.423	754^{bc}
SEM	0.66	0.28	0.082	0.57	1.50	0.44	0.38	0.011	0.023	45.2
P-value	0.26	0.0001	0.05	0.01	0.38	0.005	0.05	0.13	0.67	0.003
Post-ensiling										
Jiroft	22.8	20.0^{bc}	2.83	22.3^{ab}	39.1	13.7^{b}	2.37	0.303	0.402	485^{b}
Anbarabad	23.0	23.4^{a}	3.35	20.3^{bc}	38.8	17.3^{a}	2.76	0.300	0.398	542^{a}
Rudbar	23.6	19.3^{cd}	3.32	23.8^{a}	37.7	17.9^{a}	2.38	0.269	0.427	398^{c}
Kahnuj	22.1	21.6^{ab}	3.47	22.1^{ab}	40.9	17.7^{a}	2.82	0.276	0.441	512^{ab}
Faryab	20.5	17.8^{de}	3.22	22.9^{ab}	42.2	16.9^{a}	2.14	0.309	0.397	372^{c}
Manujan	21.8	17.2^{e}	3.47	18.3c	37.7	17.0^{a}	1.79	0.304	0.426	421^{bc}
SEM	0.64	0.51	0.11	0.72	1.54	0.34	0.34	0.033	0.027	28.6
P-value	0.14	0.002	0.07	0.02	0.36	0.003	0.39	0.92	0.72	0.004
Pre-ensiling	20.4^{b}	20.4^{a}	3.36	19.3^{b}	37.5	16.5	8.20^{a}	0.703^{a}	0.415	808^{a}
Post-ensiling	22.3^{a}	19.9^{b}	3.28	21.6^{a}	39.4	16.7	2.38^{b}	0.294^{b}	0.407	455^{b}
SEM	0.10	0.08	0.15	0.58	0.78	0.18	0.27	0.09	0.008	31.3
P-value	0.001	0.001	0.71	0.02	0.12	0.75	<0.0001	<0.0001	0.52	<0.0001

DM: Dry matter, CP: Crude protein, EE: Ether extract, NDF: Neutral detergent fiber, ADF: Acid detergent fiber, WSC: Water-soluble carbohydrates, SEM: Standard error of the mean.
[a–b:] Within column, means with common superscript(s) do not differ (P>0.05).

Table 2. Fermentation characteristics of potato haulm silages

	pH	Ammonia N (g/kg total N)	Lactic Acid (g/kg DM)	Acetic Acid (g/kg DM)	Propionic Acid (g/kg DM)	Butyric Acid (g/kg DM)
Jiroft	4.01	51.8^{ab}	65.9	17.8	0.42	0.19
Anbarabad	3.71	53.2^{ab}	69.2	16.9	0.31	0.25
Rudbar	4.77	49.0^{bc}	64.2	17.2	0.34	0.22
Kahnuj	4.37	54.3^{a}	67.5	17.6	0.37	0.22
Faryab	4.62	45.9^{c}	64.3	17.7	0.41	0.21
Manujan	4.65	48.6^{bc}	63.7	16.9	0.38	0.24
SEM	0.27	1.51	1.86	0.35	0.05	0.15
P-value	0.15	0.02	0.31	0.62	0.58	0.41

SEM: Standard error of the mean.
[a–b:] Within column, means with common superscript(s) do not differ (P>0.05).

In vitro fermentation parameters

The values of DMD, DOMD and ME in fresh PoH were significantly affected by location (Table 3). The DMD value of pre-ensiled PoH differed significantly among locations, averaging 60.8% and ranging from 58.3% (Faryab) to 64.0% (Jiroft). The mean OMD before ensiling was 70.6% and showed a trend toward location effects. The average DOMD was 56.9%, with significant differences between locations. Pre-ensiling ME averaged 2.14 Mcal/kg DM and ranged from 2.05 Mcal/kg DM (Faryab) to 2.28 Mcal/kg DM (Jiroft), with significant differences among locations. Following ensiling, all digestibility parameters decreased significantly. The DMD declined from 60.8% to 56.6%, OMD from 70.6% to 66.7%, DOMD from 56.9% to 52.3%, and ME from 2.14 to 2.00 Mcal/kg DM. Location effects on post-ensiling digestibility were significant for DMD, but showed only trends for OMD and DOMD.

Table 3. Digestibility of potato haulms pre- and post-ensiling

	DMD	OMD	DOMD	ME
Pre-ensiling				
Jiroft	64.0[a]	72.7	60.7[a]	2.28[a]
Anbarabad	63.5[ab]	74.3	59.5[ab]	2.24[a]
Rudbar	59.9[bc]	70.3	55.8[b]	2.10[b]
Kahnuj	60.3[abc]	71.2	56.0[b]	2.10[b]
Faryab	58.3[c]	66.7	54.7[b]	2.05[b]
Manujan	58.7[c]	68.2	54.8[b]	2.06[b]
SEM	1.15	1.49	1.33	0.06
P-value	0.02	0.09	0.01	0.01
Post-ensiling				
Jiroft	59.7[a]	71.1	55.2	2.11
Anbarabad	57.0[ab]	66.4	52.9	2.03
Rudbar	56.3[b]	67.6	51.5	1.97
Kahnuj	56.7[ab]	67.1	52.3	2.00
Faryab	55.6[b]	66.2	51.0	1.95
Manujan	54.1[b]	61.7	50.4	1.93
SEM	0.92	1.59	1.29	0.23
P-value	0.03	0.07	0.09	0.43
Pre-ensiling	60.8[a]	70.6[a]	56.9[a]	2.14[a]
Post-ensiling	56.6[b]	66.7[b]	52.3[b]	2.00[b]
SEM	0.35	0.41	0.38	0.01
P-value	<0.0001	<0.0001	<0.0001	<0.0001

DMD: Dry matter digestibility (%), OMD: Organic matter digestibility (%), DOMD: Digestible organic matter in dry matter (%), ME: Metabolizable energy (Mcal/kg DM), SEM: Standard error of the mean.
[a–b:] Within column, means with common superscript(s) do not differ (P>0.05).

Discussion

Chemical composition of fresh PoH

The mean DM content of fresh PoH (20.4% DM) was consistent with values reported by Koli et al. (2019; 16.81%) and within the range reported by Kaplan et al. (2018; 15–25% DM) for leafy forages at late vegetative to early reproductive stages. The variation among locations likely reflects differences in soil moisture, harvest timing, and temperature during the pre-harvest period (Abbasi et al., 2018) across the diverse regions of Kerman Province.

The CP concentrations observed in the present study (mean 20.4%) substantially exceeded those reported by Kaplan et al. (2018) for Turkish PoH cultivars (10.85–14.48% DM) and by Malecky et al. (2017) for PoH from Hamadan province, Iran (14.7% DM). The elevated CP levels may be attributed to the relatively high soil fertility and intensive irrigation management practices employed in these southern Kerman locations, which promote vigorous vegetative growth and leaf protein accumulation (Ma et al., 2024). The significant variation in CP among locations underscores the importance of regional characterization when formulating diets containing PoH (Riaz et al., 2025).

The mean EE content of fresh PoH (3.36% DM) was consistent with values reported by Koli et al. (2019; 3.50% DM) and Hosseinabadi et al. (2026; 5.20% DM), indicating a moderate lipid fraction. The ash concentrations observed in the present study (mean: 19.3% DM) was consistent with values reported for fresh PoH (5.22-9.10% DM; Kaplan et al., 2018) and processed PoH (20.8% DM; Malecky et al., 2017). This elevated and variable ash content is characteristic of PoH harvested from diverse soil types and likely reflects differences in mineral uptake from the soil, particularly calcium, potassium, and phosphorus (Nag et al., 2017). Hosseinabadi et al. (2026) similarly reported high ash content in PoH from Iran, corroborating the notion that Iranian PoH is particularly mineral-rich compared to PoH from other regions.

The NDF and ADF contents of fresh PoH averaged 37.5% and 16.5% DM, respectively, which are considerably lower than those reported by Kaplan et al. (2018) for Turkish cultivars (NDF: 47.99–60.91%; ADF: 22.46–33.94%). The relatively low fiber concentrations observed in the present study, in combination with high CP, indicate a nutritive profile superior to many conventional types of roughage and comparable to medium-quality legume hays (NRC, 2001). Malecky et al. (2017) similarly noted that PoH had lower NDF compared to alfalfa hay, which partially explained the favorable digestibility outcomes observed in fattening lambs.

The WSC concentrations across locations (7.06–9.05% DM; mean 8.20%) were at the lower threshold of the 8–12% DM range generally considered adequate for successful fermentation without additives (McDonald et al., 2022). The relatively low WSC concentrations in some locations (particularly Manujan and Rudbar) suggested a risk of restricted fermentation (Gao et al., 2021), though as demonstrated in the fermentation results, adequate lactic acid concentrations were ultimately achieved across all locations.

Nitrate content in pre-ensiled PoH averaged 0.703% DM, which was lower than the toxic level of 1% DM reported by Aiello (1998) for ruminants. These values are consistent with the low-to-moderate nitrate concentrations typical of vegetative potato tissue.

However, nitrate concentrations in the upper range of this interval warrant caution, as factors such as rapid diet change, high nitrogen fertilization, and environmental stress can exacerbate nitrate accumulation in potato foliage (Schrenk et al., 2020).

Oxalate content averaged 0.415% in pre-ensiled PoH and remained essentially unchanged following ensiling. Oxalates are antinutritional factors that can chelate divalent cations, particularly calcium, and form insoluble calcium oxalate crystals, thereby reducing mineral bioavailability and potentially contributing to renal toxicity and hypocalcemia in ruminants (Zayed et al., 2025). The oxalate concentrations observed in the present study are relatively low compared to those reported for other oxalate-rich forages such as amaranth (1.02-3.54%; Rezaei et al., 2009; Abbasi et al., 2012). Furthermore, ruminants possess a greater capacity than monogastric animals to tolerate dietary oxalates due to microbial degradation in the rumen and adaptation mechanisms (Rahman et al., 2013).

Effect of ensiling on chemical composition

Ensiling induced a modest increase in DM content from 20.4% to 22.3%, attributable to effluent loss, partial dehydration, and the conversion of soluble organic components to volatile fermentation products (Wróbel et al., 2023). Similarly, Guo et al. (2020) observed an increase in DM after ensiling potato vines with rice bran and corn, which they attributed to the loss of fermentable carbohydrates and water-soluble fractions during the anaerobic process.

The CP content decreased slightly from 20.4% to 19.9%, likely attributable to proteolysis during the initial stages of ensiling and the conversion of soluble proteins to non-protein nitrogen compounds (Jayanegara et al., 2019). However, the magnitude of CP loss was relatively modest, suggesting that fermentation conditions were favorable and that extensive protein degradation was prevented by the rapid decline in pH (McDonald et al., 2022).

The increase in ash content following ensiling reflects the concentration effect, as organic matter was lost during fermentation and the mineral fraction was retained (Muck et al., 2018). The NDF content increased, while ADF content remained essentially unchanged. The slight increase in NDF may be attributed to the loss of soluble cell contents during fermentation, resulting in a relative concentration of structural carbohydrates (Ni et al., 2017). The stability of ADF content suggests that cellulose and lignin were not significantly degraded during the ensiling process, which is consistent with the limited cellulolytic activity under anaerobic acidic conditions (Borreani et al., 2018).

The dramatic decrease in WSC after ensiling (from 8.20% to 2.38% DM) is indicative of active homofermentative lactic acid fermentation and is directly reflected by the high concentration of lactic acid produced (63.7–69.2 g/kg DM). The WSC depletion pattern is consistent with well-preserved silages and indicates active homofermentative lactic acid fermentation (Okoye et al., 2023). Similarly, Zhou et al. (2019) reported that ensiling potato vines with higher moisture content facilitated greater WSC utilization and lactic acid production, confirming the critical role of WSC availability and moisture in enhancing the fermentation quality of silage PoH.

Ensiling reduced nitrate content by approximately 58% (from 0.703% to 0.294% DM). This substantial reduction is consistent with previous reports indicating that nitrate levels typically decline by 40-60% during well-managed ensiling (Bai et al., 2022; Hülsemann et al., 2025). The post-ensiling nitrate levels observed in the present study was less than the toxic level (i.e., >6 g/kg of DM) for animals (Radostits et al., 2007). The reduction in nitrate during ensiling is mediated by several mechanisms: 1) denitrification by facultative anaerobic bacteria under acidic conditions, 2) conversion of nitrate to nitrite and subsequently to ammonia by bacterial nitrate reductase and nitrite reductase enzymes, and 3) dilution effects from effluent losses (Bai et al., 2022).

The lack of significant reduction in oxalate content during ensiling is consistent with the chemical stability of oxalic acid under anaerobic acidic conditions, as oxalate is not readily metabolized by LAB or other silage microorganisms (Murru et al., 2017). However, the absolute concentrations remain low enough that, when PoH silage is fed as a component of a balanced diet rather than as the sole feedstuff, the risk of oxalate toxicity is minimal.

Ensiling induced a significant and substantial reduction in GAs content. This reduction is consistent with the findings of Olson et al. (2001) and can be attributed to acidic hydrolysis and microbial degradation during fermentation. Under anaerobic acidic conditions, lactic acid bacteria and other silage microflora can promote the cleavage of the glycoalkaloid sugar moieties, converting α-solanine and α-chaconine to the less toxic aglycone solanidine (Schrenk et al., 2020; Wei et al., 2025). Furthermore, the low pH (mean 4.36) and high lactic acid environment created favorable conditions for this hydrolytic degradation.

Silage fermentation characteristics

The mean pH of PoH silages across locations (4.36; range: 3.71-4.77) was slightly above the 3.8-4.2 range considered optimal for well-preserved silages (McDonald et al., 1991), yet comparable to the pH of 4.5 reported by Nkosi and Meeske (2010) for untreated potato hash silage and consistent with the 4.55–6.42 range reported by Koli et al. (2019) for PoH ensiled alone or with oat. The higher pH relative to well-preserved grass or corn silages is attributable to the inherently high buffering capacity of PoH, which results from its substantial ash (19.3%) and protein (20.4%) content, both of which require greater lactic acid production to achieve equivalent pH reductions (Okoye et al., 2023). Furthermore, the DM content of the ensiled material (22.3%) is relatively low, and higher moisture silages generally require lower pH values for stable preservation (Borreani et al., 2018).

The mean ammonia nitrogen concentration was relatively low (45.9-54.3 g/kg total nitrogen), indicating moderate proteolysis during ensiling (Kung et al., 2018). The significant variation among locations may reflect differences in initial CP concentration, plant protease activity, and the rate of pH decline, with slower acidification (as suggested by higher pH in Rudbar and Manujan) allowing greater proteolytic degradation (Tao et al., 2012). Nevertheless, even the highest NH_3N value (54.3) is well below the 100-120 g/kg total nitrogen threshold commonly associated with extensive protein degradation and poor silage quality (McDonald et al., 1991).

Lactic acid concentrations were consistently high across all locations (63.7-69.2 g/kg DM), indicating uniform homofermentative fermentation across the diverse agro-climatic zones sampled. These values substantially exceed the 3–5% DM threshold indicative of good fermentation quality (McDonald et al., 1991) and are markedly higher than the 0.02% lactic acid reported by Koli et al. (2019) for PoH ensiled alone in India, where insufficient WSC severely limited LAB activity. The high lactic acid production achieved in the present study, despite the relatively low WSC concentrations in fresh PoH, suggests that the fermentable substrate was efficiently utilized, possibly due to the presence of epiphytic lactic acid bacteria adapted to the local agro-environmental conditions (Cheng et al., 2022).

Acetic acid concentrations were moderate and relatively uniform (16.9-17.8 g/kg DM), representing approximately 20-25% of total fermentation acids, a ratio consistent with desirable heterofermentative activity that contributes to aerobic stability without excessive DM loss (Ferrero et al., 2021). Nkosi and Meeske (2010) similarly reported moderate acetic acid levels in well-preserved potato-based silages, attributing this to the presence of facultatively heterofermentative LAB species alongside homofermentative strains.

Propionic and butyric acid concentrations were extremely low across all locations (<0.5 g/kg DM). The virtual absence of butyric acid (<0.25 g/kg DM) is particularly noteworthy, as it indicates minimal clostridial activity and confirms that the silages were not subject to secondary, undesirable fermentation (Kung et al., 2018). Clostridial spoilage is a common concern in low-DM, low-WSC silages (Zheng et al., 2018), and the absence of butyric acid in the present study suggests that the rate of pH decline was sufficiently rapid to suppress clostridial growth, despite the relatively high moisture content of the PoH (Li et al., 2020).

In vitro digestibility parameters

The mean DMD (60.8%) and OMD (70.6%) of pre-ensiled PoH across locations was higher than those reported for cereal straws and comparable to high-quality grass hays (NRC, 2001), confirming that PoH represents a medium-to-high quality roughage source for ruminants. High digestibility indicates the influence of chemical composition on in vitro degradability, particularly the lower NDF and higher CP concentrations, which are known to facilitate greater ruminal fermentation efficiency (McDonald et al., 2022). The ME content of pre-ensiled PoH averaged 2.14 Mcal/kg DM, which exceeds the ME requirements for maintenance in most ruminant species (1.32-1.44 Mcal/kg DM; Souza et al., 2025) and indicates that PoH can serve as an effective energy source in ruminant diets (Galla et al., 2020).

Following ensiling, all digestibility parameters decreased compared to fresh PoH. The reduction in digestibility following ensiling is a well-documented phenomenon and can be attributed to several factors (Kazemi et al., 2019; Aloba et al., 2022). First, the loss of soluble, highly digestible cell contents (sugars, organic acids, soluble proteins) during fermentation reduces the proportion of readily fermentable substrates (Du et al., 2019). Second, the formation of fermentation acids, particularly lactic acid, while beneficial for preservation, contributes to ash content and reduces the OM fraction available for digestion (Kung et al., 2018). Third, the Maillard reaction between reducing sugars and amino acids during the initial heating phase can form indigestible complexes, although the extent of this reaction is likely limited given the relatively low temperatures achieved during PoH ensiling (Borreani et al., 2018).

Despite the reduction in digestibility, the post-ensiling values remain nutritionally acceptable. The ME content of PoH silages (2.00 Mcal/kg DM) is comparable to the values reported for maize silage (2.19-2.33 Mcal/kg DM) and alfalfa hay (1.96 Mcal/kg DM) by NRC (2001). The DMD of 56.6% is also within the range considered adequate for maintaining body condition in non-lactating ruminants and supporting moderate growth rates in growing animals when supplemented with adequate protein and minerals (NRC, 2001).

Conclusions

In conclusion, the present study demonstrated that potato haulm silage from Kerman Province, Iran, could constitute a nutritionally valuable, fermentatively stable, and toxicologically acceptable feed resource for ruminants in semi-arid regions. The ensiling process effectively reduced the two primary antinutritional factors, GAs and nitrate, while preserving the substantial protein and energy content of the fresh potato haulm. The present findings suggested that potato haulm silage could represent a promising feed resource for ruminants in potato-producing areas of Iran. However, further *in vivo* feeding trials are needed to evaluate animal performance and health status before its widespread practical application can be recommended.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgement

The authors would like to thank the Department of Animal Science at South Kerman Agriculture Research, Education and Natural Resources Center and the Department of Animal Sciences at Bu-Ali Sina University for their institutional support during the preparation of this manuscript. We also extend our gratitude to the researchers whose published work formed the foundation of this conceptual framework.

Disclosure statement

The authors declare that they have no financial or personal relationships with individuals or organizations that could inappropriately influence or bias the content of this manuscript.

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