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Environmental Technology & Innovation 40 (2025) 104508

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Integrated rumen-animal-manure analysis of dairy emission mitigation by feeding apple pomace and hempseed cake

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A R T I C L E I N F O

Keywords:
Circular nutrition
Environmental emissions
Dairy sector
Sustainability

A B S T R A C T

Agri-food by-products are underused feed resources with the potential to reduce dairy emissions, yet most studies examined rumen and manure stages separately, which mask whole-system effects and shift environmental burdens between stages. This study is the first to assess the effects of incorporating apple pomace (AP) and hempseed cake (HC) into dairy cow diets on nitrogen and methane (CH_4) emissions, across the entire milk production chain, from rumen fermentation to downstream manure storage. A 3 (treatments) x 3 (Periods) Latin square design was used with 15 cows, treatment diets included (1) CON (control diet): basal diets with forage and concentrates; (2) AP: 10 % of AP replacing forage; (3) HC: 10 % of HC replacing concentrates. Faeces and urine outputs were collected separately from animals, for manure storage experiment. Feeding AP and HC decreased ($P < 0.01$), respectively, enteric CH_4 production by 6.3 % and 6.7 %, CH_4/feed intake by 10.6 % and 10.1 %, and CH_4/milk yield by 9.8 % and 10.9 %. Inclusion of AP decreased urine N /total N intake, compared to CON and HC ($P < 0.05$). In manure storage, the AP decreased the cumulative ammonia (NH_3) and CH_4 emissions by 24.8 % and 27.4 % than CON, respectively ($P < 0.05$). The above mitigation actions through feeding AP and HC, when working together in implementation for feeding dairy cows, could decrease annual CO_2 equivalent emissions by 13 % and 10 % respectively. This is the first integrated study combining rumen fermentation with manure impacts, showing that AP and HC inclusion can be a practical approach to mitigate emissions in dairy farming.

1. Introduction

Livestock production system substantially contributes to the essential diets for human but inevitably results in considerable emissions of ammonia (NH_3), methane (CH_4) and nitrous oxide (N_2O). The NH_3 production cause a series of issues that include particulate matter ($PM_{2.5}$) formation, eutrophication, soil acidification and habitat loss, thus posing significant impacts on human health and ecosystem (Steinfeld, 2006). The CH_4 and N_2O are potent greenhouse gases (GHG), with global warming potentials (GWP)

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https://doi.org/10.1016/j.eti.2025.104508
Received 27 June 2025; Received in revised form 29 August 2025; Accepted 11 September 2025
Available online 12 September 2025

approximately 28 and 273 times greater than carbon dioxide (CO_2) over a 100-year time horizon (IPCC, 2019). Emissions of those gases occur throughout the production chain: from animal production to manure management. CH_4 is primarily attributed by the enteric fermentation of ruminant livestock, accounting for 30 % of global anthropogenic CH_4 emissions (CCAC, 2021). Manure storage emits around 70 % of global anthropogenic NH_3 emission, and a certain amount of N_2O and CH_4. Environmental emissions from the livestock sector are thus acknowledged to be mitigated imperatively (De Haan et al., 1997; Gerber et al., 2013).

Research on reducing emissions from the livestock production primarily focusing enteric fermentation in ruminants has made significant progress, particularly in nutritional interventions. Strategies include the use of novel feedstuffs or additives in diets such as tannin-containing feeds, plant leaves and seaweed. Seaweed (*Asparagopsis taxiformis*), has been shown to reduce enteric CH_4 emissions by up to 80 % in dairy trials without causing negative effect on animal performance (Kinley et al., 2020; Roque et al., 2021). Studies demonstrated that dietary inclusion of tannin-rich plants can reduce enteric CH_4 emissions by 15–50 %, depending on the type and dose of tannin (Jayanegara et al., 2012; Patra and Saxena, 2011). An inclusion of vine leaves at 130 g/kg DM produced 20 % less CH_4 than basal diet (Birkinshaw et al., 2022). Although feeds are typically not incorporated into manure, the use of additives during manure storage has been increasingly tested and showed feasibility in reducing emissions. Bacillus-based biological additives combined with aeration reduced CH_4 emissions by up to 67 % and NH_3 by 90 % during slurry storage, while natural sorbents like biochar and zeolite mixtures mitigated NH_3 emissions by 42 % from cattle faeces (Ali et al., 2022; El bied et al., 2024).

The disposal of agri-food by-products also poses a large environmental problem. Apple pomace (AP), by-product of apple juice and cider production, contain energy-rich, fibrous and palatable ingredients and has a large-scale production globally, making it an ideal option for inclusion in diets across various livestock species. Several studies have shown its high feasibility as a feedstuff in dairy, beef and goat (Fang et al., 2016; Fayed, 2019; O'Shea et al., 2012), with inclusion levels set at 100–200 g/kg dry matter (DM). Hempseed cake (HC), a by-product of hemp seed oil extraction, as a protein-rich feed ingredient that can be effectively included in ruminant diets. Similar to AP, inclusion of HC to replace protein-rich ingredients at levels at 100–200 g/kg DM in diets did not negatively impact and even improve animal performance (Jacobson et al., 2021; Rapetti et al., 2021; Winders et al., 2022).

Novel feedstuff or additives with high concentration of bioactive compounds have shown potential in reducing enteric CH_4 emissions (Hristov, 2024). AP is particularly enriched in polyphenols—procyanidin (condensed tannin), chlorogenic and catechin. HC, by contrast, is characterized by phenolic amides and lignanamides, with tocopherols, phytosterols, and residual polyunsaturated lipids; these constituents can suppress methanogenesis and, through tannin–protein complexation, alter rumen-degradable protein and downstream N partitioning (Gadulrab et al., 2023; Martinez et al., 2020; Waldbauer et al., 2017). However, the enteric CH_4 mitigating effects of ensiled AP and dried HC are rarely reported. More importantly, the integration of emissions from slurry and enteric fermentation has not been sufficiently investigated. By-products with bioactive compounds may influence N partitioning in animals, thereby altering N and bioactive compound content of excreta. (Kebreab et al., 2006; Petersen et al., 2013). Evaluating stages in isolation can mischaracterize whole-farm emission outcomes because dietary interventions that reduce enteric CH_4 might influence the gas emission during manure storage. Zhang et al. ((2019) reported significant decrease in enteric CH_4 but higher faecal and urine N was also observed, which is likely to cause higher production of NH_3, CH_4 and N_2O. Understanding these downstream impacts is essential to ensure that dietary interventions contribute to minimizing overall emissions in livestock production systems (Fitriyanto et al., 2017; Svane and Karring, 2022).

Using ensiled AP and HC as animal feed offers a cost-effective, circular approach that turns low-value agri-food residues into measurable reductions in emissions. Evidence suggests that, when supported by strong leadership, effective knowledge sharing, and adaptable management practices, such frugal innovations can improve sustainability performance in resource-limited sectors (Achmad and Wiratmadja, 2024).

The objectives of this novel study were to i) investigate the effects of dietary inclusion of AP and HC on enteric CH_4 emission and N utilization of dairy cows, ii) monitor residual effects of AP and HC on NH_3, N_2O and CH_4 emissions during manure storage. We hypothesized that the inclusion of those by-products mitigated the CH_4 emission in the rumen, with further residual mitigation impact on the subsequent emission from manure storage.

2. Materials and methods

2.1. By-products preparation

A total of 20 tons of fresh Bramley apple pomace (AP) were collected from Davisons Quality Foods Co., Ltd (Portadown, Northern Ireland). The AP and barley straw were mixed at the ratio of 70 %: 30 % on DM basis and ensiled with additive named Silo King GS (Agri-King Inc, Ireland), in a trench silo on a concrete floor in the Agri-Food and Biosciences Institute (AFBI), Hillsborough, UK. Apple pomace silage was ensiled anaerobically for 90 days before use. The hempseed cake used in the study were acquired from the UK Hemp Co., Ltd. (Wiltshire, UK), and incorporated in diets in dry form.

2.2. Animal experiment

The feeding experiment was conducted at AFBI research farm, Hillsborough, UK. Fifteen mid-lactating Holstein dairy cows were assigned into 5 blocks based on parity (2.4 ± 0.28 lactations), lactation stage (133 ± 2.59 days in milk), milk yield (33.3 ± 1.15 kg) and body weight (607 ± 11.3 kg). The three animals within each block were then randomly allocated to the 3 treatment diets in a 3 (diet) x 3 (period) Latin Square design study with 24 d/period. Three diets (DM basis) included (1) CON: basal total mixed ration (TMR) containing 50 % concentrates, 45.7 % grass silage and 4.3 % barley straw; (2) AP: 10 % grass silage replaced by apple pomace in TMR;

(3) HC: 10 % soyabean meal replaced by hempseed cake in TMR. All diets were formulated to meet requirements of metabolizable energy and metabolizable protein for lactating cows according to Feed into Milk models (Thomas, 2004). The diets ingredients and chemical compositions are shown in Table 1. All diets were prepared daily for ad libitum intake with a 5 % target refusal rate. Concentrate pellets were offered through Greenfeed system (1 kg DM/cow/day, 4 visits per day, 9 drops/visit) and milking parlour (1 kg DM/cow/day, 0.55 kg for am and 0.55 kg for pm milking) during day 1 – 17 of each trial. During the last 7 days of each period when housed in digestibility units, 2 kg DM pellets were offered daily as top-up during the milking (1 kg in the morning and 1 kg in the afternoon).

Cows were provided with water ad libitum and TMR once a day at 1100 h. Cows were milked twice daily in a milking parlour at 0600 h and 1500 h throughout the experiment. Each period in this experiment lasted for 24 days. Fifteen cows (5 cows/treatment) were housed in the cubical accommodation as a single group with biocontrol system from day 1 to day 17. Immediately after the completion measurements in barn, the same 3 cows per treatment from the same 3 blocks were moved out and housed in individual digestibility units for 7 days, where total faeces and urine outputs were collected during the final 6 days. All cows were monitored throughout the trial to minimize bias from health events, which include daily clinical checks and sensor/production alerts.

2.3. Measurement of gas emissions from enteric fermentation of cows

Gas emissions (CH_4, CO_2, and H_2) from each cow were measured by GreenFeed system (C-Lock Inc.) from d 1 to d 17. Details of the use of GreenFeed units were illustrated by Melgar et al. (2021), The intervals between each drop were 40 s and cows were only allowed to visit the GreenFeed units every 4 h.

2.4. Experimental samplings

During day 1–24 of each period, milk yields were recorded daily, and milk samples collected at 0600 h and 1500 h were sent for component analysis. Total amount of faeces and urine were recorded daily for the final 6 days. Faeces and urine samples were taken daily that as 5 % of total weight (faeces) or volume (urine). After the sample collection in last day in each period, urine and faeces samples from each cow during six days in digestibility unit were mixed separately and were analysed of N concentrations. Other samples were dried for determine DM concentration.

During day 1–24 of each period, daily feed intakes were recorded through the BioControl feeders. Representative samples of feed were collected daily throughout the trial.

2.5. Laboratory analysis for animal experiment

Dry matters of grass silage and ensiled AP samples were determined from drying triplicated 100 g fresh samples in oven at 60 °C for 48 h, faeces samples dried at 60 °C for 6 days and concentrate samples dried at 85 °C for 24 h. All dried samples were then transferred in a muffle furnace at 550 °C for 5 h to determine organic matter (OM) content (Horwitz and Latimer, 2005). N concentration of feed and milk samples were determined using a Tecator Kjeldahl Auto 1030 Analyzer (Foss Tecator AB, Höganäs, Sweden), while faeces and urine samples were determined on fresh basis.

2.6. Manure storage experiment and its measurement of gas emissions

During the third period, the faeces and urine for manure storage experiment was collected at the day 22 of animal experiment, to ensure excreta reflected steady-state digestion under the assigned diets. The final two days served as a contingency window in case the collection in day 22 was disturbed. Faeces and urine were collected in proportion to the volumes produced on the sampling day. The

Table 1
Chemical composition of experimental diets.

Items[2]	Treatment diets[1]			AP	HC
	Control	AP[1]	HC		
DM (g/kg)	342	311	341	183	967
OM (g/kg DM)	913	925	918	972	934
CP (g/kg DM)	169	170	167	60	289
EE (g/kg DM))	36.3	40.5	41.6	46.1	92.9
NDF (g/kg DM)	402	409	420	610	359
ADF (g/kg DM)	254	273	274	514	301
WSC (g/kg DM)	53.3	49.5	44.9	9.9	23.2
NFC (g/kg DM)	186	174	148	202	193
GE (g/kg DM)	19.2	19.7	19.5	21.2	21.4
TT (mg GAE/g DM)				3.82	1.82

[1] Treatments were AP= apple pomace inclusion at the level of 10 % and HC= hempseed cake inclusion at the level of 10 %.
[2] DM, Dry matter content; OM, Organic matter content; CP, Crude protein; EE, Ether extract; NDF, Neutral detergent fiber; ADF, Acid detergent fiber; WSC, water soluble carbohydrate; GE, Gross energy; TT, Total phenolic; GAE, Garlic acid equivalent.

urine collection bucket (no acid added) was kept in a foam box filled with ice to minimize the urine N loss during collection. A total of 15 kg faeces and urine were collected from each cow for the manure gas emission trials (n = 3). The weights of faeces and urine in the 15 kg sample were calculated based on the actual proportion of faeces and urine excreted in individual cows. The faeces and urine samples were stored separately in −20 ℃ until experiment.

To simulate the local environment, the manure storage experiment was carried out in a temperature-controlled chamber maintained at 12 °C and 60 % relative humidity, with continuous ventilation at 10 m^3 / hour. Faeces and urine sample were defrosted two days before the experiment, followed by mixing and storing in containers of 37 L capacity. The mixed manure chemical properties were determined before and after the experiment upon collecting 100 g of manure samples.

The NH_3, CH_4 and N_2O emissions from 15 kg manure samples were measured at a series of timepoints, which were 0 h, 3 h, 6 h, 12 h, 24 h, 48 h, 72 h, 96 h, 1-week, 2-week, 3-week and 4-week. The measurement started at 1100h–1130 h am using static chamber technique (Baral et al., 2023). During the gas measurement period, the containers were closed with the lids for an hour after removing the air in headspace using a hair dryer. Each lid was equipped with a butyl rubber septum through which a PTFE tube was inserted. One end of each tube featured a two-way switch valve to control gas flow. During measurements, a photoacoustic analyzer (GASERA F10, Finland) was connected to the headspace of the container via PTFE tubing, with the gas flow regulated by activating the switch valve. Before sampling gas from the containers, two background air samples were collected to determine initial gas concentrations at time zero (t0). At the end of each closed period (t60), two gas measurements were taken from the containers; the average concentration from these measurements was then used to calculate flux. Air temperature, relative humidity and pressure (measured with Extech's RHT510 Hygro-Thermometer Psychrometer, Extech Instruments, Taiwan) were recorded to adjust gas concentrations in flux calculations. After each measurement, lids were partially opened to replicate typical storage conditions, allowing for air circulation and minimizing moisture loss. At the end of the trial, measurements for the volume of the slurry were conducted, to calculate the headspace of the container.

2.7. Gas flux calculations from manure storage

Daily fluxes of NH_3, CH_4, N_2O were calculated using Eq. (1) (Baral et al., 2023):

$$F(NH_3, CH_4, N_20) = \left(\frac{\mathrm{C60} - C0}{\mathrm{t60} - t0}\right) \cdot \left(\frac{\mathrm{V}M}{\mathrm{A}Vm}\right) \tag{1}$$

Where *F (NH_3, CH_4, N_2O)* is the daily flux of NH_3 or CH_4 or N_2O (mg. m^{-2} h^{-1}); *C0* and *C60* are the gas (μL L^{-1}) concentration determined at zero min (*t0*; ambient air) and at 60 min (*t60*) after closure of the containers, respectively, and the time is expressed in hour (h). *V* is the bucket headspace volume (L); *A* is the slurry surface area (m^2); *M* is the molar mass of NH_3 or CH_4 or N_2O (g mol^{-1}); and *Vm* is the volume of 1 mol of gas (L mol^{-1}) which was calculated using standard atmospheric pressure and temperature measured at the time of gas sampling.

Cumulative emission was calculated by linear interpolation from observed NH_3, N_2O and CH_4 fluxes at two adjacent timepoint.

2.8. Laboratory analysis for manure during storage experiment

Properties of manure were characterised before and after the experiment, when manures were thoroughly homogenised, and samples were drawn. Slurry DM concentration was determined from drying triplicated 20 g fresh slurry in oven at 60 ℃ for 6 days and then transferred in a muffle furnace at 550 ℃ for 5 h to determine ash content (Horwitz and Latimer, 2005). pH was measured with a pH meter (model 632 equipped with the electrode 6.0202.000 containing 3 M KCl electrolyte; Metrohm, Herisau, Switzerland) in homogenized samples at a depth of 10 cm. Total nitrogen (TN) of manure samples were determined using a Tecator Kjeldahl Auto 1030 Analyzer (Foss Tecator AB, Höganäs, Sweden). Total ammoniacal nitrogen (TAN) was analyzed using an NH_3 electrode (Orion 9512 NH3 electrode, Thermo Fisher Scientific Europe, Nijkerk, Netherlands).

2.9. Impact of implementing the present output in commercial dairy production

To understand total GHG reduction potential of feeding AP and HC in real agricultural contexts, we used the present outputs to calculate the reduction capacity in CO_2 equivalent (CO_2e), based on enteric CH_4 emissions and manure storage CH_4 and N_2O productions on a yearly basis for indoor feeding dairy cows producing 4000 to 12,000 kg milk per year. Emission data of CON group were obtained as above described and data of AP and HC group were using average reduction rate obtained in this study.

Enteric CH_4 emissions from cows fed no AP or HC was predicted using Eq. 2 (Niu et al., 2018) and Eqs. 3 and 4 (Thomas, 2004), assuming no live weight gain or loss throughout the production cycle under varying milk production scenarios (4000–12000 kg/year), while from AP or HC cows were calculated by applying the average reduction rate to total emissions from the CON cows. Representative daily milk yields and corresponding live weights, dietary metabolizable energy (ME) concentration in lactation and dry period, were presented in Table S1 of supplementary file, reflecting typical adjustments to meet rising demands. Energy requirements for maintenance, lactation, and pregnancy were estimated using Feed into Milk models (Thomas, 2004), also presented in supplementary information.

$$Predicted\ CH_4\ \ emission(g/d) = 124 + 13.3 \times \left(\frac{\mathrm{DMIlac} + DMIdry}{365}\right) \tag{2}$$

Where DMIlac and DMIdry is the total dry matter intake over the lactation period (kg) and dry period (kg) respectively.

$$DMIlac = \frac{MElac \times 315 + MEpre \times \frac{1}{3}}{MEconlac} \tag{3}$$

$$DMIdry = \frac{MEm \times 50 + MEpre \times \frac{2}{3}}{MEcondry} \tag{4}$$

Where MElac (MJ/d) is total ME requirement for maintenance and lactation, MEpre (MJ) is ME requirement for pregnancy, ME_m (MJ/d) is maintenance ME requirement in dry period, MEconlac and MEcondry are dietary ME concentration (MJ/kg DM) in lactation and dry period respectively.

Prediction of emissions from manure management for CON cows were based on IPCC guideline (IPCC, 2019), while for AP or HC cows were calculated by applying the average reduction rate to total emissions from the CON cows. The CH_4 emissions from manure were estimated using Eq. 5 (IPCC, 2019). Direct N_2O emissions from manure can be estimated using Eq. 6 (IPCC, 2019). The NH_3 emissions from manure can be estimated using Eq. 7 (IPCC, 2019). The assumption used was based on the representative farm condition: Holstein–Friesian dairy cows with high productivity in free-stall housing with scraped alley; slurry-based manure storage with cool temperate moist, also pumped to an external tank with natural crust/cover; diets (forage and grain) provided as TMR once per day and parlour herds milked twice per day.

$$CH_{4(mm)} = \left[\sum_{(T,S,P)} \left(N_{(T,P)} \times VS_{(T,P)} \times AMWS_{(T,S,P)} \times EF_{(T,S,P)}\right) \Big/ 1000\right] \tag{5}$$

Where $CH_{4(mm)}$= CH_4 emissions from Manure Management in the country, kg CH_4 yr-^{1}, $N_{(T,P)}$= number of head of livestock in the country, $VS_{(T,P)}$= annual average VS excretion per head of livestock, $AMWS_{(T,S,P)}$= fraction of total annual VS for each livestock species/category *T* that is managed in manure, $EF_{(T,S,P)}$= emission factor for direct CH_4 emissions from manure management system. S= managemenet system, T = species/category of livestock P = high or low productivity system.

$$N_2O_{(mm)} = \left[\sum_{(T,S,P)} \left(N_{(T,P)} \times Nex_{(T,P)} \times AMWS_{(T,S,P)} \times EF_{1(S)}\right) \Big/ 1000\right] \times \frac{44}{28} \tag{6}$$

Where $N_2O_{(mm)}$= N_2O emissions from Manure Management in the country, kg CH_4 yr-^{1}, $N_{(T,P)}$= number of head of livestock in the country, $Nex_{(T,P)}$= annual average N excretion per head of livestock, $AMWS_{(T,S,P)}$= fraction of total annual nitrogen excretion for each livestock species/category *T* that is managed in manure, $EF_{1(T,S,P)}$= emission factor for direct N_2O emissions from manure management system.

$$NH_{3(mm)} = \left[\sum_{(T,S,P)} \left(N_{(T,P)} \times Nex_{(T,P)} \times AMWS_{(T,S,P)}\right) \Big/ 1000\right] \times \frac{44}{28} \times EF_2 \tag{7}$$

Where $NH_{3(mm)}$= NH_3 emissions from Manure Management in the country, kg CH_4 yr-^{1}, EF_2= the proportion of NH_3 in the aggregated volatilization of N_2O and NH_3, was 0.93 as previously reported.

The CO_2 eq of CH_4 and N_2O was considered as 28 and 273 times of CO_2 respectively, as previous study reported. Total CO_2 eq was calculated as the sum of enteric CH_4, manure CH_4 and manure N_2O. Reduction rates was calculated using Eq. 8.

$$Total\ \ CO_2eq\ \ reduction\ \ rate = \frac{CO_2eq_{(T)} - CO_2eqc}{CO_2eqc} \tag{8}$$

Where $CO_2\ eq_{(T)}$= total CO_2 e emission in AP or HC group, $CO_2\ eqc$= total CO_2 eq emission in CON group.

To generalize it to large scale context, the net weight of annual environmental emissions(CO_2 and NH_3) for a 100-cow dairy farm were calculated using Eq. 9.

$$Aannual\ reduction_{(G)} = \left(Gas\ emission_{(G,T)} - Gas\ emission_{(G)}\right) \quad \times 100 \tag{9}$$

Where *annual reduction*$_{(G)}$= annual gas reduction, *Gas emissions*$_{(G,T)}$ = annual gas emissions in treatment group, *Gas emission*$_{(G)}$= annual gas emission in CON group. *G*= CO_2 or NH_3, *T* = AP or HC group.

2.10. Statistical analysis

All the data obtained were analysed using Mixed model procedure of IBM SPSS, version 22.0 (Armonk, NY, USA). Data collected from animal experiment in Latin Square Design were analysed with following model:

$Y_{ijkl} = \mu + T_i + P_j + B_k + E_l + T_i \times P_j + E_{ijkl}$,

Where Y_{ijk} was observation of the dependent variable; μ was overall mean; Ti was fixed effect of treatment; P_j was fixed effect of period; B_k was random effect of the block; E_l was random effect of the individual cow; $T_i \times P_j$ was fixed effect of the interaction between treatment and period; E_{ijkl} was residual error.

Data collected from photoacoustic analyzer were for repeated measures analysis based on following model:

$Y_{ijkl} = \mu + T_i + S_j + M_k + N_l + T_i \times S_j + F_{ijkl}$,

Yik was observation of the dependent variable μ was overall mean; T_i was fixed effect of treatment; S_j was fixed effect of timepoints; M_k was random effect of the block of the manure (equal to block of cows); N_l was random effect of the individual manure l(equal to individual cows); $T_i \times S_j$ was fixed effect of the interaction between treatments and timepoints; F_{ijkl} was residual error.

Cumulative gas emission and manure properties were analyzed based on linear mixed model with treatments as fixed effect, blocks as random effect. For every model, residuals were tested for normality and variance homogeneity firstly. Post hoc multiple comparisons were conducted according to fisher's Least Significant Difference test. The results are presented as least-square means and standard error of means. Statistical differences were considered significant at $P < 0.05$ and as a tendency at $0.05 \leq P < 0.10$.

3. Results

3.1. Enteric gas emission and animal performance of dairy cows

For CH_4, there was no significant difference among diets from day 1 to day 8 (Fig. 1A) and significant difference was observed from day 12 to day 15 ($P < 0.05$). The inclusion of AP and HC significantly decreased average CH_4 production by 6.3 % and 6.7 % respectively over the last 7 days in cubical accommodation (Fig. 1B), without causing difference in CO_2 production (Fig. 1C) but reducing the CH_4 to CO_2 ratio (Fig. 1D). Significant reductions in H_2 production were observed in two diets (Fig. 1E), compared with CON ($P < 0.001$). Feed intake, milk yield and ECMY increased with feeding AP and HC (Table 2), compared to CON ($P < 0.05$). The AP reduced CH_4 production per kilogram of DMI, milk yield and ECMY by 10.6 %, 9.8 % and 10.5 % respectively ($P < 0.01$), while HC reduced those parameters by 10.1 %, 10.9 % and 11.1 % respectively ($P < 0.01$).

3.2. Nitrogen utilization of dairy cows

Presented in Table 3, significantly higher N intake ($P < 0.05$) was observed in AP, compared with CON and HC. The excretion of faecal N and milk N in both treatment group were higher than the control group ($P < 0.05$). Inclusion of HC increased faecal N and milk N output per unit of total N intake compared with CON and AP ($P < 0.05$), while inclusion of AP significantly decreased urine N output

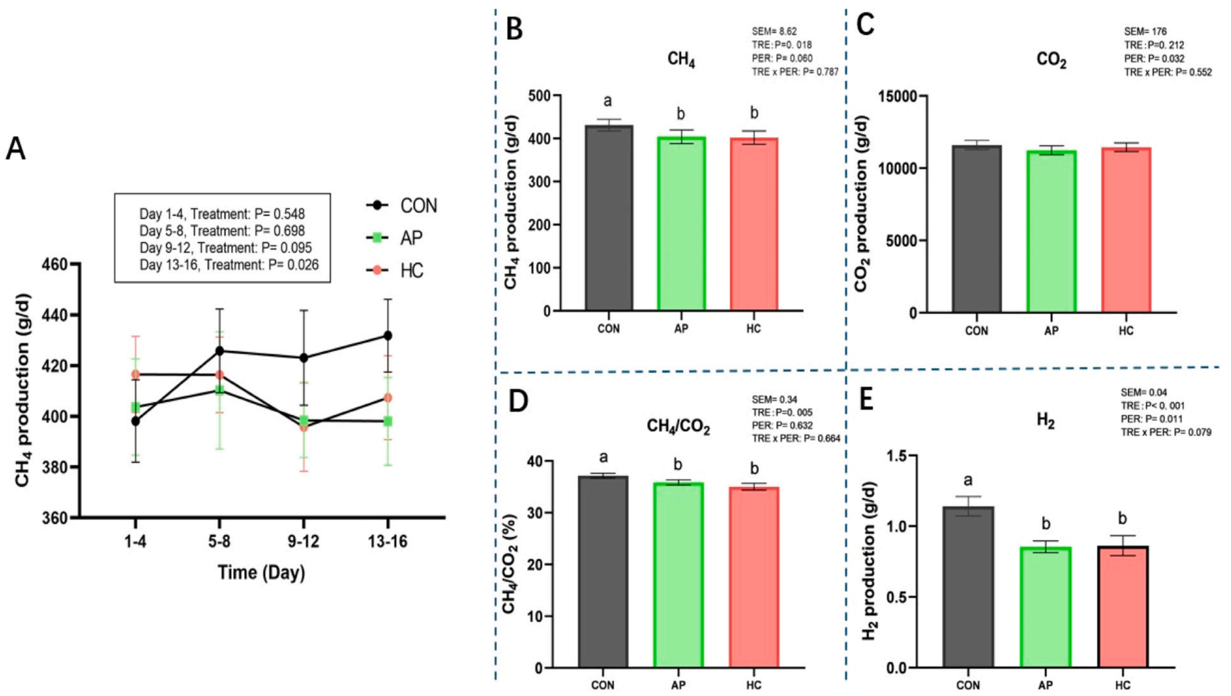

Fig. 1. Enteric methane production during the entire experimental period and the gas production at the last 7 days in cubical accommodation, of dairy cows fed diets including apple pomace and hempseed cake (CON, control diet group; AP, apple pomace group; H, hempseed cake group). (A) CH_4 production over time. (B) Average CH_4 production within the last 7 days. (C) CO_2 production (D) The ratio of CH_4 to CO_2. (E) H_2 production.

Table 2
Animal performance and enteric CH_4 emissions of lactating cows fed diets included with apple pomace and hempseed cake.

Items	Treatment[1]			SE[2]	P-value[3]		
	Control	AP	HC		Tre	Per	Tre×Per
DM intake (kg/d)	19.1[b]	20.0[a]	19.8[a]	0.29	0.045	0.288	0.113
Milk yield (kg/d)	25.1[b]	26.3[a]	26.4[a]	0.58	0.002	< 0.001	0.132
ECMY[4] (kg/d)	26.9[b]	28.4[a]	28.4[a]	0.62	0.003	< 0.001	0.135
CH_4 emission intensities							
CH_4/Feed intake (g/kg)	22.7[a]	20.3[b]	20.4[b]	0.43	< 0.001	0.562	0.080
CH_4/Milk yield (g/kg)	17.4[a]	15.7[b]	15.5[b]	0.42	< 0.001	< 0.001	0.242
CH_4/ECMY (g/kg)	16.2[a]	14.5[b]	14.4[b]	0.39	< 0.001	< 0.001	0.238

[a,b] Significant differences between diets are indicated with different superscript letters ($P < 0.05$)
[1] Treatments were AP= apple pomace inclusion at the level of 10 % and HC= hempseed cake inclusion at the level of 10 %.
[2] SE, Standard error of mean.
[3] Tre, treatment; Per, period; Tre x Per, the interaction between treatment and period.
[4] ECMY, Energy-corrected milk yield, which was calculated using the equation : ECMY= (Milk yield x milk energy concentration)/ (0.0384 fat + 0.0223 crude protein + 0.0199 lactose - 0.108)

Table 3
Nitrogen utilization efficiency of lactating cows fed diets included with apple pomace and hempseed cake.

Items	Treatment[1]			SE[2]	P-value[3]		
	Control	AP[1]	HSC		Tre[3]	Per	Tre×Per
N intake (g/d)	484[b]	519[a]	496[b]	6.82	0.001	0.002	0.563
N output (g/d)							
Fecal N	156[b]	168[a]	167[a]	3.02	0.014	0.003	0.454
Urine N	191	180	177	6.08	0.347	0.026	0.545
Manure N	347	348	344	7.48	0.943	0.001	0.471
Milk N	136[b]	149[a]	150[a]	3.00	0.001	0.004	0.231
N balance	0.74	23.4	1.31	7.36	0.108	< 0.001	0.281
N partitioning (% N intake)							
Fecal N	32.2[b]	32.3[b]	33.7[a]	0.47	0.055	< 0.001	0.548
Urine N	39.4[a]	34.6[b]	35.9[ab]	1.18	0.086	0.028	0.303
Manure N	71.6	66.8	69.6	1.31	0.104	0.001	0.223
Milk N	28.2[b]	28.7[b]	30.3[a]	0.58	0.031	0.001	0.135
N balance	0.21	4.50	0.10	1.51	0.126	< 0.001	0.287
N excretion as a proportion of milk yield (g/kg)							
Fecal N/Milk yield	6.58	6.51	6.34	0.12	0.301	0.002	0.808
Urine N/Milk yield	8.10[a]	7.00[b]	6.78[b]	0.30	0.014	0.012	0.353
Manure N/Milk yield	14.7[a]	13.5[b]	13.1[b]	0.38	0.007	0.001	0.307
N excretion as a proportion of ECMY[4] (g/kg)							
Fecal N/ ECMY	5.79	5.73	5.74	0.10	0.879	0.009	0.294
Urine N/ ECMY	7.10[a]	6.17[b]	6.10[b]	0.24	0.036	0.037	0.318
Manure N/ ECMY	12.9[a]	11.9[b]	11.9[b]	0.30	0.034	0.006	0.222

[a,b] Significant differences between diets are indicated with different superscript letters ($P < 0.05$)
[1] Treatments were AP= apple pomace inclusion at the level of 10 % and HC= hempseed cake inclusion at the level of 10 %.
[2] SE, Standard error of mean.
[3] Tre, treatment; Per, period; Tre x Per, the interaction between treatment and period.
[4] ECMY, Energy-corrected milk yield.

per unit of total N intake compared with CON and HC ($P < 0.05$). Inclusion of AP decreased urine and manure N excretion as a proportion of milk yield by 13.8 % and 8.2 %, and inclusion of HC decreased those parameters by 16.3 % and 10.9 %. Inclusion of AP decreased urine and manure N excretion as a proportion of ECMY by 13.0 % and 7.8 %, and inclusion of HC decreased those parameters by 14.0 % and 7.8 %.

3.3. Manure properties

Properties of the manure prior to and after the manure storage experiment were presented in Table 4. For DM, OM, pH, TN and TAN, there was no significant difference among diets at the beginning of the manure storage. After the trial, the residual DM in AP manure was higher than that in CON and HC manure ($P < 0.05$). The residual OM in both AP and HC manures were significantly higher than that in CON manure ($P < 0.01$). After the trial, a greater TN was found in AP manure, compared to HC and CON manure ($P < 0.05$). Lower pH was found for AP at the end of the trial, compared with HC and CON ($P < 0.05$). The TAN was not affected by the inclusion of by-products.

Table 4
Properties of manure collected from cows fed with different diets at the start and at the end of the storage.

Items[2]	Treatment[1] Control	AP	HC	SE[3]	P-Value
DM (g/kg FM)					
Begin	84.1	93.3	88.2	2.20	0.255
End	103[b]	120[a]	109[b]	2.93	0.027
OM (g/kg DM)					
Begin	852	856	863	2.39	0.173
End	764[b]	812[a]	811[a]	8.77	0.007
pH					
Begin	8.45	8.37	8.42	0.03	0.604
End	7.58[a]	7.30[b]	7.44[ab]	0.05	0.019
TN (g/kg FM)					
Begin	5.59	5.74	5.65	0.12	0.903
End	3.71[b]	4.51[a]	4.18[ab]	0.14	0.039
TAN (g/kg FM)					
Begin	3.98	3.62	4.18	0.17	0.435
End	3.57	3.51	3.76	0.12	0.611

[a,b] Significant differences between diets are indicated with different superscript letters ($P < 0.05$)
[1] Treatments were AP= apple pomace inclusion at the level of 10 % and HC= hempseed cake inclusion at the level of 10 %.
[2] DM, Dry matter content; OM, Organic matter content; TN, total nitrogen content; TAN, total ammoniacal nitrogen content.
[3] SE, Standard error of mean

3.4. Gas emission during manure storage

Treatment, measurement time and their interaction had significant effects on fluxes of NH_3, CH_4 and N_2O flux ($P < 0.05$). Differences were found in NH_3 flux among diets (Fig. 2A), where AP has significantly lower emissions than HC and CON ($P < 0.05$) while there was no difference between HC and CON. Inclusion of AP reduced the cumulative NH_3 by 24.8 % than CON ($P < 0.05$) (Fig. 2B), but HC increased by 4.1 % although not statistically significant ($P > 0.05$). For CH_4, differences were significant among diets (Fig. 2C), where AP was lower than HC and CON while there was no difference between HC and CON ($P < 0.05$). Inclusion of AP decreased the cumulative CH_4 by 27.4 % than CON ($P < 0.05$) (Fig. 2D). Dietary inclusion of AP and HC (Fig. 2F) decreased cumulative N_2O by 4.7 % and 2.3 % respectively. Dietary inclusion of AP significantly decreased emission factor TN ($P < 0.01$), relative to HC and CON (Table 5).

3.5. Impact of implementing the present output in commercial dairy production

Feeding AP and HC decreased CO_2e emissions per kg milk by 13 % and 10 % respectively (Fig. 3A). The enteric CH_4, manure CH_4 and N_2O in each group were shown in Fig. 3 B, C and D. Feeding AP and HC could reduce respectively 45,339 kg and 34,518 kg CO_2e emission for a 100-cow dairy farm with annual milk yield at 4000 kg, and the reduction of CO_2e increased with the growth of milk yield (Fig. 4A). Feeding AP in cows diets reduced 293 kg NH_3 emission for a 100-cow dairy farm with annual milk yield at 4000 kg, and the reduction of NH_3 weight increased with the growth of milk yield (Fig. 4B).

4. Discussion

The environmental footprint of livestock production, particularly dairy farming, is increasingly under scrutiny due to its substantial contributions to GHG emissions and NH_3 volatilization. These emissions not only exacerbate climate change but also impact soil, water and air quality. Mitigating these emissions without compromising animal productivity is a critical challenge for sustainable livestock management. This study evaluates for the first time the effectiveness of dietary inclusion of AP and HC, two agro-industrial by-products, on GHG and NH_3 emissions from dairy cows, addressing both enteric and downstream manure-related emissions. The present findings provide insights into the dual role of these by-products feeds in reducing environmental impact while supporting dairy productivity.

4.1. CH_4 emissions from enteric fermentation and manure storage

Significant differences in CH_4 emissions were observed only between days 12 and 15, which could be explained by the rumen adaptation period. After a diet switch, the rumen microbial consortia (protozoa–methanogen symbioses, fibrolytics) typically need about 7–14 days to re-equilibrate. During days 1–9, CH_4 output is in transition and highly variable, masking between-diet contrasts (Machado et al., 2016). Feeding AP and HC in the present study significantly reduced enteric CH_4 emissions by 6.3 % and 6.7 % respectively, consistent with previous research highlighting the potential of dietary interventions to mitigate enteric CH_4 emissions through alterations in ruminal fermentation (Beauchemin et al., 2020; Firkins et al., 2013). The observed decrease in CH_4 to CO_2 ratio in the rumen also suggests improved fermentation efficiency and a shift in ruminal microbial activity as CH_4 output is a source of

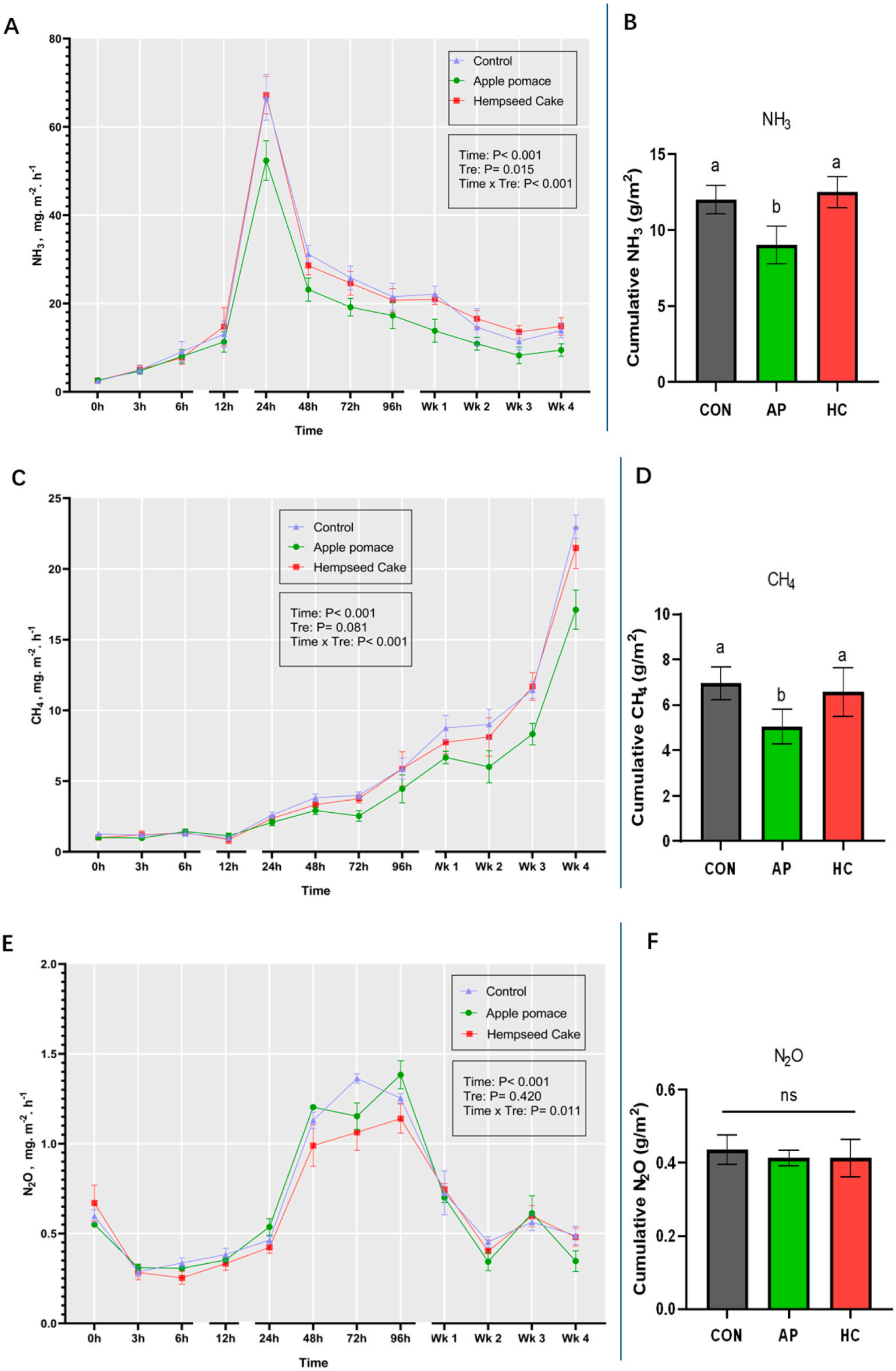

Fig. 2. The effects of dietary inclusion of apple pomace and hempseed cake on NH_3, CH_4 and N_2O emission of manure (CON, control diet group; AP, apple pomace group; H, hempseed cake group). (A) Temporal dynamics of NH_3 flux. (B) Cumulative NH_3 emission during experiment. (C) Temporal dynamics of CH_4 flux. (D) Cumulative CH_4 emission during experiment. (E) Temporal dynamics of NO_2 flux. (F) Cumulative NO_2 emission during experiment. Bars represent mean values and error bars represent standard errors of mean. Different letters represent significant differences among the dietary groups at $P < 0.05$.

Table 5
Emission factors (EFs) during the manure storage period.

Items[3]	Treatment[1]			SE[2]	P-Value
	Control	AP	HC		
EF TN (%)	14.3[a]	10.5[b]	14.8[a]	0.74	0.004
EF TAN (%)	20.1	16.8	20.2	0.82	0.246

[a,b] Significant differences between diets are indicated with different superscript letters ($P < 0.05$)
[1] Treatments were AP= apple pomace inclusion at the level of 10 % and HC= hempseed cake inclusion at the level of 10 %.
[2] SE, Standard error of mean.
[3] TN, total Nitrogen; TAN, Total ammoniacal nitrogen.

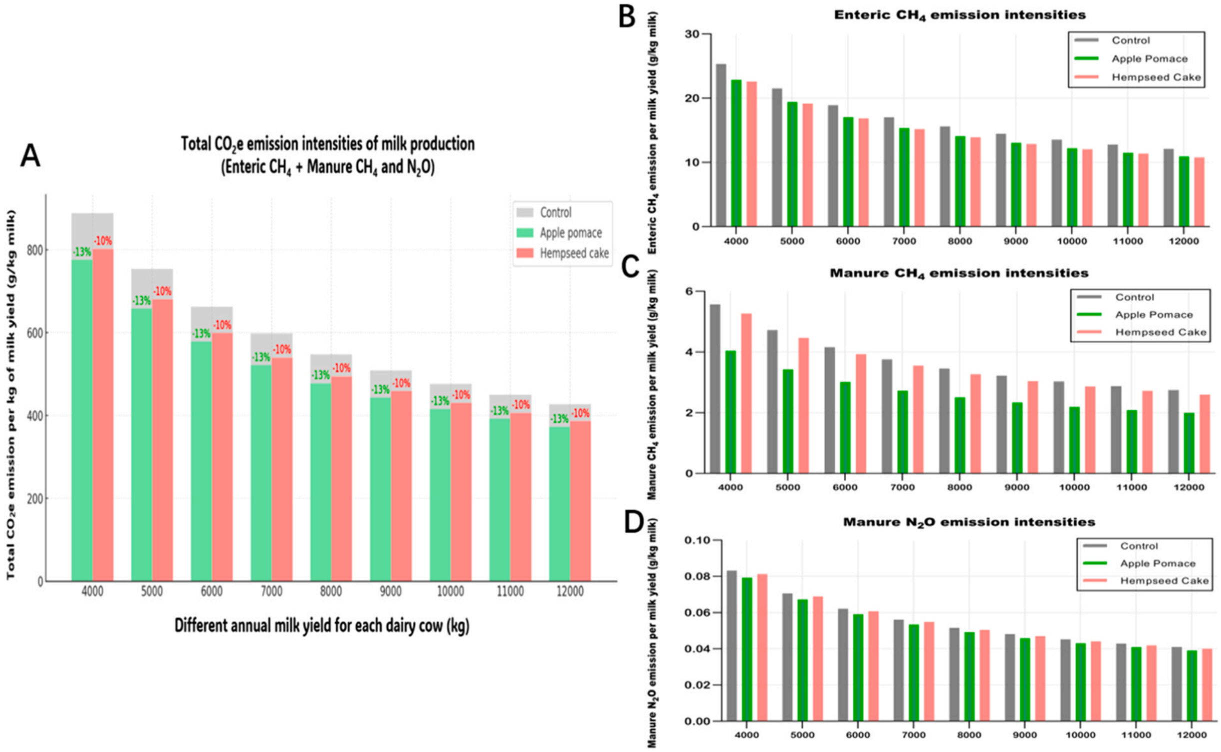

Fig. 3. Total and partition of CO_2e emission per milk yield for cows with different milk yields. (A) Total CO_2e emission per milk yield. (B) CO_2e emission from enteric CH_4 per milk yield. (C) CO_2e emission from manure CH_4 per milk yield. (D) CO_2e emission from manure N_2O per milk yield.

energy loss in dairy cows (Iqbal et al., 2008). Additionally, reductions in rumen H_2 production in both treatment groups indicate modifications in hydrogen utilization pathways, potentially favoring alternative sinks over methanogenesis, which supports the results of reduction on CH_4 (Olijhoek et al., 2016). These results are potentially explained by studies demonstrating the effectiveness of polyphenol- and phytochemical-rich by-products in reducing CH_4 emissions by influencing rumen microbiota, potentially leading to decreased methanogenesis (Patra and Saxena, 2010). Apple pomace, for instance, contains polyphenols that can modulate microbial activity. Similar mitigating-effects were reported by previous study, where 150 g/kg DM of dried apple pomace led to an 8 % reduction in CH_4 emissions (Gadulrab et al., 2023). In line with other fruit by-products, Moate et al. (2014) and Akter et al. (2025) reported that grape pomace and grape marc reduced CH_4 emissions by 11 % and 20 % at the inclusion level of 150 and 270 g/kg DM. The slight disparity in reduction rates might stem from differences in the bioactive compounds present in apple and grape, as grape are richer in tannins and polyphenols that suppress methanogenesis by inhibiting methanogenic archaea and redirecting H_2 to alternative pathways (Min et al., 2003). Another possible reason responsible for the disparity is the dietary inclusion level and fat content. Lower inclusion level and less fat content caused the less reduction on CH_4, as every 10 g/kg DM of increase in fat content, CH_4 production can be decreased by up to 3.8 % (Martin et al., 2010). As far as fat content, grape diet is 32 g/kg DM higher than its control diet while apple diet in this study is only 4.2 g/kg DM higher than control diet (Moate et al., 2014). Similar to HC in this study, the use of high-oil rapeseed cake in dairy cow diets has been demonstrated to decrease CH_4 emissions. Previous studies found that replacing conventional feed with rapeseed cake reduced CH_4 emissions per kg of DMI by 7.1 % and per kg of energy-corrected milk by 12.4 %, while enhancing milk production and feed efficiency, suggesting its potential as a feed ingredient, which is in favour of the environmental

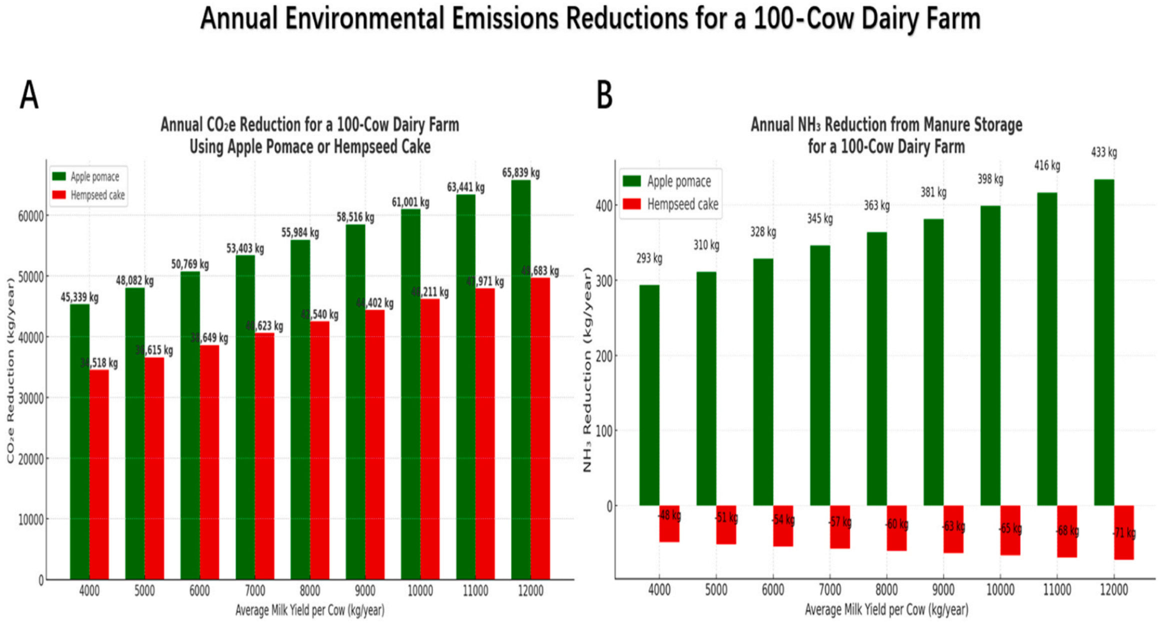

Fig. 4. Annual CO_2e and NH_3 reduction for a 100-cow dairy farm with different milk yield. (A) Annual CO_2e reduction for a 100-cow dairy farm with different milk yields. (B) Annual NH_3 reduction for a 100-cow dairy farm with different milk yields.

sustainability of these interventions (Bayat et al., 2022; Karlsson et al., 2010). The more significant reduction in CH_4 emissions per kg DMI and milk yield further underscores the efficacy of these by-products, potentially addressing the dual challenge of balancing productivity with environmental impact, which is critical for sustainable livestock systems (Eckard et al., 2010).

In the present study, CH_4 emissions during the later stages (after 2 weeks) of manure storage occurred primarily due to the anaerobic decomposition of OM by methanogenic archaea or bacteria. As manure storage progresses, oxygen contents decrease, creating an anaerobic environment that facilitates the activity of microorganisms. Over time, the establishment of anaerobic conditions enhances CH_4 production (Baral et al., 2018). The 27.4 % reduction in cumulative CH_4 emissions from AP group manure in the present study could be attributed to several mechanisms. Firstly, high contents of polyphenols in AP might play a crucial role in mitigating CH_4 production during manure storage through inhibition of methanogens and reduction of hydrogen availability (Patra and Saxena, 2010), consistent with the study where CH_4 reduction was caused by the use of polyphenols extracted from coffee grounds and rapeseed press cake (Svane and Karring, 2022). Unlike to their method, which involved mixing of manure with extraction, this study didn't add any additives in manure. The second effect of polyphenols could be the stabilization of OM as observed in this study. The OM content of manure in AP group was significantly higher compared to the control at the end of the manure experiment though similar OM contents in the manure of these two groups at the beginning of the manure trial, indicating higher degradation of OM in the manure in control group. The polyphenols bind proteins and carbohydrates in OM, reducing their bioavailability for microbial decomposition and restricting the substrate pool for methanogenesis, thereby decreasing CH_4 production (Mueller-Harvey, 2006). Secondly, reduction of CH_4 could be caused by manure N content through microbial competition and inhibition of methanogenesis. Specifically, ammonia-oxidizing bacteria compete with methanogens for substrates, such as ammonium (NH_4^+) and organic carbon, in the manure environment (Adesogan et al., 2013). Elevated NH_3 concentrations, particularly in the form of free NH_3, can be toxic to methanogens, inhibiting activity in methanogens, reducing their capacity to produce CH_4 (Rajagopal et al., 2013; Wang et al., 2015). This is supported by results in this study, showing TN content in AP group is higher than control.

4.2. Nitrogen utilization of dairy cows and N_2O and NH_3 emissions during manure storage

Efficient N utilization in dairy cows is critical for both enhancing productivity and mitigating environmental impacts. There were significantly higher feed intake and N intake observed in the AP and HC group compared to CON, so it is expected to observe the higher milk and fecal N excretion related to CON. Intriguingly, no difference was found in daily urinary N output among all groups, which reflects a redistribution of N partitioning, so the reduction in urinary N excretion per unit of total N intake in AP group is particularly noteworthy. The decrease in urinary N excretion observed with AP inclusion might be attributed to several factors. Firstly. urinary N is primarily derived from N losses in the rumen (Tamminga, 1992). The presence of bioactive compounds in AP, such as tannin, may influence N metabolism by binding to proteins and affecting their degradation thereby decrease the production of NH_3-N (Powell et al., 2009). The less protein available for rumen microorganism would reduce the excess of NH_3-N in the rumen. Unutilized NH_3-N by rumen microorganism is absorbed through the ruminal epithelium into the bloodstream, where it is subsequently converted to urea in the liver and excreted in urine (Van Soest, 1994). Consistent with present findings, Broderick et al. (2008) reported a reduction in urinary N excretion associated with increased N intake, a pattern that parallels the observations of the current study. Our results are supported by another study in which no significant difference in urinary N output was observed; however, cows receiving grape marc excreted less urinary ammonia (Greenwood et al., 2012). Secondly, this is in line with a previous study that fed cows distillers grains with solubles, which also reported a similar reduction in urinary N (Gehman and Kononoff, 2010). Another significant source of urinary N is the incomplete conversion of absorbed amino acids for productive functions such as tissue growth and milk protein synthesis (Tamminga, 1992). Reduced ruminal N losses and urinary N excretion in AP group is likely due to enhanced conversion of absorbed AA into milk and tissue protein. In the present study, milk N increased from 136 to 149 g/d, and retained N improved from −0.74 to 23.4 g/d for diets including AP. These findings suggest a more efficient utilization of amino acids (AA) for productive purposes, coupled with reduced deamination and urinary excretion of N from surplus AA. In the present study, feeding HC increased milk nitrogen output and reduced N loss, suggesting potential differences in N utilization and metabolic pathways. These results differ from other studies, which reported that feeding hempseed did not improve milk N output but led to greater N retention in body tissues, potentially due to the diverse bioactive compounds (Bayat et al., 2022; Rapetti et al., 2021; Winders et al., 2023). These differences highlight the potential of dietary strategies to enhance nitrogen use efficiency (NUE), an important metric for assessing the sustainability of dairy systems. Higher NUE indicates that a greater proportion of dietary nitrogen is converted into productive outputs (e.g., milk) rather than being lost to the environment (Gerber et al., 2013).

In the present study, NH_3 emissions exhibited considerable variability both within and among the treatment diets throughout the measurement period. Emissions from the manure of the AP group were significantly lower at certain time points between 24 h and 4 weeks, after which emissions in all groups tended to return to their initial levels. Notably, cumulative NH_3 emissions during manure storage reduced by 24.8 % in the AP group compared to control. Several factors could be responsible for it. Firstly, from the perspective of biochemistry, urinary N is a major contributor to NH_3 emissions during manure storage, through microbial breakdown of urinary urea and rapidly hydrolysed to NH_3 (Erisman et al., 2011; Mangwe et al., 2024). The present findings are consistent with studies showing that dietary intervention could shift nitrogen excretion from urine to feces, thereby mitigating NH_3 volatilization. This is because N in urine is mainly urea, quickly converting to ammonia and nitrate, while N in faeces is mainly organic, releasing slowly (Powell et al., 2010). The emissions of NH_3 from manure were also impacted by pH by influencing the equilibrium $NH_3 + H^+ = NH_4^+$ transformation (Li et al., 2015). Higher pH tends to shift the equilibrium toward NH_3. In the present AP diet, lower emissions of NH_3 were related to lower pH of manure compared to control and HC (Table 5). The higher TN in AP and HC than CON also indicates that the OM transformation was lower as evident in this experiment. The N stabilization indicates retention of nitrogen as NH_4^+ rather than NH_3, further mitigating emissions. Similar N stabilization has been reported previously with reduced dietary crude protein (Sajeev et al., 2018; Tan et al., 2023); however, dietary CP contents were formulated to be similar in this study.

Intriguingly, reduction of NH_3 by 57 % was found in a study that included another type of apple pomace in diets, which is 2-fold higher than this study (24.8 %), potentially attributed by the higher dose (300 g/kg DM vs 100 g/kg DM) (Mao et al., 2017). Secondly, from the perspective of physical barrier, AP likely created a denser and more compact crust due to its fibrous nature. The fibrous matrix of AP, derived from the cellulose and lignin components, could have physically impeded the diffusion of NH_3 from the manure to the atmosphere (Chadwick, 2005). This physical layer effect is particularly effective in reducing NH_3 emissions early during storage, as observed in the significant differences at 24–72 h in the present study. A thicker manure surface also supports the development of anaerobic zones, where the conversion of NH_4^+ to NH_3 is less favourable due to lower oxygen availability. This aligns with findings from previous study (Misselbrook et al., 2005), that reported reduced NH_3 emissions in manure systems with thicker or crusted surfaces. All of these explains are evidenced by the DM and OM of slurry properties.

4.3. *Practical implication*

Our research experiment used controlled conditions with a single herd, which limits direct extrapolation to all farm contexts. Emission magnitudes from stored manure vary with infrastructure (e.g., open lagoons vs. covered/closed tanks), climate/season (temperature and storage duration), and herd characteristics (breed, productivity). Open systems typically favour higher NH_3 volatilisation, and covering/closing stores reduces NH_3 while effects on CH_4/N_2O depend on cover type and conditions (Kupper et al., 2020; Mohankumar Sajeev et al., 2018). Warmer storage generally increases microbial activity and CH_4 formation, whereas colder seasons suppress it; regional and seasonal variation is captured in IPCC methane conversion factor. (Cárdenas et al., 2021; IPCC, 2019). Despite system-dependent absolute fluxes, enteric CH_4 intensity reductions are system-independent, and for storage, lower urinary N input and pH (AP group) plus possible polyphenolic inhibition mean the sign of NH_3/CH_4 mitigation is expected to persist; only the size of the effect varies with manure system and climate. (Montes et al., 2013). Breed differences can alter baseline emissions through intake, milk yield and physiology, with some studies showing contrasts (e.g., Holstein vs. Jersey) while others report similar CH_4 per unit DMI or ECM; therefore, absolute values may shift with breed, but relative treatment effects expressed per unit DMI or milk should be transferable (Münger and Kreuzer, 2006; Uddin et al., 2021).

Most of those studies in dairy production primarily focused on enteric CH_4 emissions, with limited follow-up analysis of emissions originating from manure, so these studies often did not report the impact of implementing these mitigation strategies on total CO_2-equivalent emissions from enteric fermentation and manure storage in a whole production system. Even though prediction might be done through life cycle assessment (LCA) based on model and equation (March et al., 2021), data analysis from actual experiment is scarce. This limitation poses a challenge for comprehensive comparison, as total environmental impact assessments require accounting for the full spectrum of emissions along the manure management pathway. For instance, in a very similar study, inclusion of food processing industrial by-products in diets at the level from 600 to 800 g/kg DM (Alqaisi et al., 2014), CO2e emissions/100 kg milk were reduced by 14 %-16 % in different scenarios, close to the reduction rate from enteric fermentation and manure stage in the present study (10 % and 13 %). However, this LCA study took various variables into account and data were not obtained from actual experiment, so the comparison would be not meaningful enough.

By-products typically classified as food waste generate disposal costs and can impose environmental burdens if not properly managed. Repurposing them as livestock feed can reduce the carbon footprint linked to both feed production and waste disposal, while promoting a circular economy by turning waste into valuable feed resources. Apple pomace (AP) supplies are abundant but seasonal and largely concentrated near juice or cider processing facilities. Due to its high moisture content and perishable nature, AP is most economically handled through wet processing and rapid ensiling close to the source. Although drying can stabilize the product, it is energy-intensive and rarely cost-competitive without access to low-cost heat (Gołębiewska et al., 2022; Tulej and Głowacki, 2022).

For processors, disposal or handling fees vary by contract. In some anaerobic digestion (AD) markets, gate fees are low or even negative, making AP available at a low plant-gate cost where AD capacity exists nearby. These considerations define realistic supply radii, influenced by spoilage risk and transport costs, and highlight the need for covered on-farm storage (Golecha and Gan, 2016; Satchwell et al., 2018). Hemp cake (HC) availability is growing but remains region-specific and less abundant than conventional oilseed meals. Its use requires compliance with EU regulations ($\leq$0.3 % THC; certified varieties) and routine quality assurance to monitor residues and nutritional variability (Capcanari et al., 2023).

Overall, while substantial volumes are available, cost-effective use is most feasible where dairies are located close to processors, with ensiling facilities and clear procurement arrangements in place—conditions that align with the circular economy approach outlined above.

5. Conclusion

The present study demonstrated that dietary inclusion of AP and HC in dairy cow rations effectively reduced enteric CH_4 production and improved animal performance. Moreover, AP could further contribute to less ammonia and CH_4 emission during manure storage. Both by-products enhance nitrogen utilisation efficiency in dairy cows, as inclusion of AP caused a N excretion shift from urine to faeces, while HC caused a higher milk N output.

Overall, the use of AP and HC in dairy cow diets represents a strategy with significant potential for reducing atmospheric pollutants from the livestock sector. These by-products not only diminish enteric CH_4 emissions but also lower nitrogen losses during manure storage, contributing to environmental sustainability while enhancing animal productivity. Future research should focus on (i) techno-economic analysis considering feed price volatility, by-product logistics, ensiling/drying losses, and potential revenue (milk, quality premiums, carbon/air-quality credits); (ii) A farm-to-gate LCA that consider displaced environmental burdens from more various fields.

CRediT authorship contribution statement

Xianjiang Chen: Resources, Investigation. **Benchu Xue:** Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Tianhai Yan:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Sokratis Stergiadis:** Supervision, Resources, Investigation. **Theodoridou KATERINA:** Writing – review & editing, Visualization, Supervision, Methodology, Funding acquisition. **Omar Cristobal-Carballo:** Resources. **Laurence Smith:** Writing – review & editing. **Khagendra Raj Baral:** Writing – review & editing. **Azadeh Dabiri:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgements

The provisions of by-products from suppliers and the assistance from staff in Queen's University Belfast and Agri-food and Biosciences Institute are gratefully acknowledged. Financial support for this work has been provided by the Biotechnology and Biological Sciences Research Council (BBSRC) [grant number BB/T008776/1] as part of the Doctoral Training Partnership FoodBioSystems: biological processes across the Agri-Foodsystem from pre-farm to post-fork.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2025.104508.

Data availability

Data will be made available on request.

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