Soybean Oil vs. Palm Oil Calcium Soap Supplementation: Effects on Milk Yield and Methane Emissions in High-Yielding Dairy Cows

CRISTINA CASTILLO[1]*, ELENA N. MARTÍNEZ[1], RODRIGO MUIÑO[1], GHASAQ SAMI MSHARY[1,2], JOSÉ MARÍA VIANA[3], JOAQUÍN HERNÁNDEZ[1]

[1] Departamento de Patoloxía Animal, Facultad de Veterinaria de Lugo, Campus Terra-IBADER, Universidad de Santiago de Compostela, Spain.
[2] Department of Physiology, Chemistry and Pharmacology, College of veterinary medicine, AL-Muthanna University
[3] Animal Nutrition Company AIRA SCG, 27550 Lugo, Spain

SUMMARY

This observational field study evaluated the effects of dietary lipid supplementation with soybean oil and palm oil-based calcium soaps on milk yield, composition, in high-yielding Holstein-Friesian dairy cows under real-world commercial conditions representative of intensive European dairy systems. Conducted across four commercial dairy farms, the study assessed four distinct fat supplementation strategies: soybean oil (70 g/kg dry matter [DM]), and palm oil calcium soap at three inclusion levels (150, 210, and 250 g/kg DM). A total of 335 multiparous cows were followed throughout a full 305-day lactation period.

All cows were fed a basal total mixed ration (TMR) formulated in accordance with NRC (2001) guidelines, with fat supplementation incorporated into the concentrate. Milk yield was recorded daily, and samples were analyzed for fat, protein, -hydroxybutyrate (BHB), milk urea nitrogen (MUN), somatic cell count (SCC), and detailed fatty acid (FA) profiles. Enteric methane emissions were estimated, not directly measured, using the IPCC Tier-2 model with methane conversion factors (Ym) adjusted for lactation status. This approach provides a practical estimation of environmental impact based on dry matter intake and energy conversion, though it does not capture animal-level variation.

Due to the study's observational design and lack of experimental replication-each farm applied a unique supplementation protocol-statistical comparisons were not conducted. Instead, results are presented descriptively and interpreted with caution, reflecting real-world variability in genetics, management, and environment.

Among the tested strategies, moderate supplementation with palm oil calcium soap (150 g/kg DM) achieved a favorable balance between productivity and environmental efficiency, showing intermediate milk yield and the lowest methane emission intensity per kilogram of milk. In contrast, higher levels of palm oil supplementation (210 and 250 g/kg DM) were associated with increased milk yield and fat content, but also higher methane emissions. The soybean oil group exhibited the lowest milk yield but similar methane intensity to the 150 g/kg palm oil group, indicating potential for environmental sustainability despite lower productivity.

Fatty acid analysis revealed that increasing palm oil supplementation led to a higher proportion of saturated and trans fatty acids, while moderate levels favored a more balanced FA profile. Principal Component Analysis (PCA) and Pearson correlation analysis showed clear associations between milk yield, milk fat, trans FA, and methane intensity, suggesting that the type and level of fat supplementation can influence both productive and environmental parameters.

While causal inference is limited, the findings provide practical insights into climate-smart nutritional strategies applicable to commercial dairy systems. Further controlled trials are warranted to validate these associations and optimize fat supplementation protocols for both productivity and environmental sustainability.

KEY WORDS

Fat supplementation; dairy cows; milk yield; methane emissions; commercial farms; palm oil calcium soap; soybean oil.

Introduction

Milk composition and environmental sustainability have become central concerns in modern dairy production, influencing not only the nutritional and technological quality of dairy products but also the sector's overall ecological footprint and its societal acceptance. The fatty acid (FA) profile of milk is a key determinant of its nutritional value and technological functionality, with important implications for human health (1, 2, 3), modifying the fatty acid composition of milk has long been recognized as a strategy to enhance its nutritional value for human health (4). At the same time, the dairy industry faces growing pressure to reduce greenhouse gas (GHG) emissions, particularly methane (CH_4), a potent contributor to global

*Corresponding Author:
Cristina Castillo (cristina.castillo@usc.es)

warming largely produced via enteric fermentation in ruminants (5, 6). Nutritional strategies, especially the inclusion and balance of specific fatty acids, have emerged as practical tools to address these challenges.

At the same time, the dairy industry faces mounting pressure to reduce greenhouse gas (GHG) emissions, particularly methane (CH_4), which is a potent contributor to global warming largely produced via enteric fermentation in ruminants (5, 6). Nutritional strategies, particularly the inclusion and balance of specific dietary fatty acids, have emerged as one of the most practical and effective strategies to address these challenges.

Numerous studies have demonstrated that manipulating dairy cow rations to include or balance specific fatty acids can significantly alter milk components such as total fat and protein, as well as the detailed spectrum of milk fatty acids (7, 8, 9). Major advances in dairy nutrition have underscored the role of dietary fat supplementation in modulating milk composition (10). These dietary manipulations not only improve milk nutritional quality, but also have the potential to reduce methane emissions, thereby supporting the transition toward sustainable dairy production systems (3, 11).

It is important to note that this study was conducted in real commercial settings, in which the inherent variation in genetics, management, housing, and environmental conditions cannot be fully controlled. Each farm was assigned a distinct fat supplementation strategy, reflecting actual production realities rather than experimental replicates, and thus limiting causal inference. Therefore, findings should be interpreted as descriptive and exploratory, providing practical insight into potential associations under commercial conditions and laying the groundwork for future controlled and replicated studies (12).

MATERIALS AND METHODS

Animals, diets, and husbandry

This investigation was conducted on four commercial Holstein-Friesian dairy farms located in Galicia (NW Spain), each housing approximately 100 lactating cows. Farms were selected based on the 2019 Refinement to the 2006 IPCC Guidelines, targeting herds with annual productivity exceeding 8,500 kg per cow and diets with digestibility (DE%) greater than 70%, calculated as DE (MJ/kg) divided by gross energy (GE, MJ/kg) multiplied by 100. All diets contained less than 35% neutral detergent fiber (NDF) on a dry matter (DM) basis.

Prior to study initiation, all lactating cows underwent systematic clinical examination focusing on body condition score, body temperature, thorax, abdomen, and mammary gland, following procedures described by Nelson et al. (13). Only cows meeting the predefined health and management criteria were included in the study.

A total of 335 multiparous Holstein-Friesian cows (mean body weight: 700 ± 50 kg) were enrolled. Average daily milk yield ranged from 38 to 40 kg per cow, corresponding to an annual yield of 11,590–12,200 kg/cow over a standardized 305-day lactation period. During peak lactation (150 days postpartum), dry matter intake (DMI) ranged from 24 to 27 kg/cow/day. The study covered the entire lactation phase (305 days), ending prior to the dry-off period.

Each treatment was implemented in a different commercial dairy farm, distributed as follows:

Farm A: 70 g/kg of dry matter (DM) of soybean oil (70-SO)
Farm B: 150 g/kg DM of palm oil calcium soap (150-PO-CS)
Farm C: 210 g/kg DM of palm oil calcium soap (210-PO-CS)
Farm D: 250 g/kg DM of palm oil calcium soap (250-PO-CS).

The chemical composition of the diets for each experimental group is detailed in Table 1. Following calving and throughout lactation, cows were fed a basal diet in the form of total mixed ration (TMR), consisting of corn silage, grass silage, and a formulated concentrate, ensuring nutrient supply in accordance with NRC 2001 (14) recommendations for lactating cows. Diets were designed to maintain high productivity while providing the specific fat supplementation for each group.

Table 1 - Chemical composition of diets for cows in the different experimental groups (DM basis for all components except DM content, which is expressed on a fresh matter basis).

Parameter	70-SO	150 PO-CS	210 PO-CS	250 PO-CS
DM (g/kg fresh matter)	528	459	488	495
aNDFmo (g/kg DM)	298.5	319.8	327.0	323.9
ADF (g/kg DM)	193.2	210.2	215.1	208.4
ADL (g/kg DM)	31.5	34.1	36.0	30.1
NFC (g/kg DM)	325.2	301.5	269.4	279.7
Starch (g/kg DM)	241.7	249.3	218.2	233.0
CP (g/kg DM)	167.1	162.4	150.5	161.3
EE (g/kg DM)	38.0	34.0	37.2	36.2
Ash (g/kg DM)	72.1	77.5	84.6	70.3

Abbreviations: DM, dry matter; aNDFmo, neutral detergent fiber analyzed with heat-stable amylase and including residual ash; ADF, acid detergent fiber; ADL, acid detergent lignin; NFC, non-fiber carbohydrate; CP, crude protein; EE, ether extract content. Note: Values are presented as mean ± standard error. No statistical comparisons were performed due to the observational design (one farm per treatment). Differences are to be interpreted descriptively.

Cows were milked twice daily (07:00 and 18:00) using 2×12 herringbone parlors on all farms. The Friesian Breeders Association recorded milk production data. (https://www.africorlugo.com), an authorized entity responsible for daily yield recording. Animals were identified using farm codes, bovine identification numbers, and calving dates, allowing for accurate determination of total milk yield. Raw milk parameters analyzed in this study included fat, protein, BHB, MUN, and SCC. Somatic cell count was included as an indicator of udder health, given its practical utility in dairy cows (15).

Experimental Design and Study Limitations

The implementation of treatments in commercial farms, each representing one unique combination of dietary fat supplementation, is representative of typical production conditions in Galicia but precludes strict causal attribution of observed differences to the nutritional intervention alone. Each farm served as one experimental unit for its respective treatment; thus, potential confounding variables such as genetics, management, and environment could not be fully controlled. Such design mirrors commercial realities but limits replication and statistical inference; results should therefore be interpreted as descriptive, in accordance with current best practices (1, 7).

Lipid extraction from raw milk

The fatty acid (FA) profiles of homogenized raw milk samples were determined according to the method described by Barreiro et al. 2018 (16). Samples were analyzed either immediately upon receipt or after storage for no longer than 4 weeks at -25°C.

Briefly, 10 L of milk was mixed with 2 mL of 2.5% sulfuric acid (H SO) in methanol, vortexed for 1 minute, and left overnight at 4°C to ensure efficient lipid extraction and derivatization. This simultaneous extraction and methylation procedure minimizes sample handling and reduces potential losses.

Following this, samples were incubated in a water bath at 60°C for 2 hours for fatty acid methylation. Methyl nonadecanoate was used as an internal standard to account for variations in extraction efficiency and instrumental response, essential for accurate quantification expressed as milligrams per 100 milliliters.

Fatty acid methyl esters (FAMEs) were extracted with 1 mL of n-hexane and subsequently separated via gas chromatography (GC), considered the gold standard for FA profiling, using an Agilent 6850 GC system equipped with a flame ionization detector (GC-FID) and a DB-Wax capillary column (60 m length, 0.25 µm internal diameter, 0.25 µm film thickness; Agilent Technologies, Santa Clara, CA, USA).

The chromatographic conditions were as follows: oven temperature was initially held at 35°C for 2 minutes, then ramped to 100°C at 30°C/min, followed by an increase to 225°C at 5°C/min, and finally held at 225°C for 10 minutes. The injector and detector temperatures were set at 250°C and 300°C, respectively. Helium was used as the carrier gas at a flow rate of 1.8 mL/min with a split ratio of 10:1. Data acquisition was performed with GC ChemStation software version B.03.02 (Agilent Technologies).

Chromatograms were carefully examined to ensure proper peak integration and identification. The proportion of each FA was calculated as the peak area divided by the total area of all identified FAs and expressed as a percentage by weight.

Calibration was performed using the Supelco 37 Component FAME Mix (Sigma-Aldrich, St. Louis, MO, USA) to guarantee accurate identification and quantification of individual fatty acids.

All samples were analyzed in duplicate, and mean values were used for the final data analysis. Results are expressed in mg per 100 mL of milk.

Estimation of methane emissions

The enteric methane emissions factor (CH4-EF) was estimated using the methane conversion factor (Ym %) values as proposed by Appuhamy et al. 2016 (17), Jayasundara et al. 2016 (18), which contributed to the Tier-2 model proposed by the International Panel on Climate Change (IPCC) in its latest 2019 Refinement to the 2006 IPCC Guidelines (19). A Ym value of 5.7% was applied for lactating cows, while a value of 6.3% was used for cows in the dry-off phase, following subsequent research (20).

The equation employed to determine the levels of enteric methane emissions is presented below (19).

$$EF = \frac{[GE \times (Ym/100) \times 305\ (DIM)]}{55.65\ MJ/kg\ CH_4}$$

where EF represents the CH_4 emission factor (kg CH_4/head/305 days in milk, DIM), and 55.65 (MJ/kg CH_4) is the energy content of methane.

Methane emissions were not measured directly. Instead, estimated methane output was calculated using the specify the equation/model used, e.g., IPCC guidelines, published predictive equations, etc., based on intake and/or milk production parameters. This approach provides an estimation, not a direct measurement, and should be interpreted with caution.

2.5. Statistical analysis

The effect of lipid supplementation on milk production and composition variables was assessed using descriptive statistics, in accordance with the observational nature of the study. The variables analyzed included daily milk yield (DMY), dry matter intake (DMI), methane emissions per kilogram of milk per day (CH_4-EF/kg milk/day), milk fat and protein content, -hydroxybutyrate (BHB), milk urea nitrogen (MUN), somatic cell count (SCC), saturated fatty acids (SFA; including short-, medium-, and long-chain fatty acids), and unsaturated fatty acids (UFA; including monounsaturated MUFA, polyunsaturated PUFA, and trans fatty acids TFA).

Each dietary treatment was applied on a separate commercial dairy farm representing independent production units with their own management, genetics, and environment. These farms were not experimental replicates but reflected real-world production variability.

To explore relationships among variables, Pearson correlation analysis was performed to examine the strength and direction of linear associations between milk production parameters, composition, and fatty acid profiles. This analysis helped identify significant pairwise relationships that could indicate underlying biological connections.

Additionally, an exploratory Principal Component Analysis (PCA) was conducted using standardized values of six key variables: daily milk yield, methane emissions per kilogram of milk, milk fat and protein content, milk urea nitrogen, and trans fatty acids. PCA aimed to reduce data dimensionality and visualize patterns of similarity or separation among the four dietary groups.

All statistical analyses were performed using R software (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Our results are presented as descriptive statistics. Due to the observational design, differences observed between groups should be interpreted cautiously, as other unmeasured factors may contribute to the observed outcomes.

Nutritional Parameters

Descriptive differences were observed between treatment groups in several nutritional components of the diets, as shown in Table 1. The 70-SO group had numerically higher dry matter (DM), non-fiber carbohydrates (NFC), and crude protein (CP) contents compared to the palm oil calcium soap (PO-CS) groups. In contrast, the 210-PO-CS group presented the highest values for acid detergent fiber (ADF), acid detergent lignin (ADL), and ash content. The 150-PO-CS and 250-PO-CS groups showed intermediate values across most parameters. Neutral detergent fiber (aNDFmo), starch, and ether extract (EE) content remained relatively consistent across groups. These differences may reflect both the characteristics of the fat supplements and specific feeding practices at each commercial farm.

As each dietary strategy was implemented in a different farm, these observations should be interpreted as descriptive and not as direct effects of the dietary fat supplementation.

Productive parameters and environmental indicators
Table 2 presents the descriptive results for feed intake, milk yield, and estimated methane emissions.

Table 2 - Feed intake, milk yield, and estimated methane emissions in each group.

Variable	70-SO	150-PO-CS	210-PO-CS	250-PO-CS
DMI (g/Kg)	19.25±0.81	20.17±0.87	20.11±0.85	20.69±0.89
DMY (Kg/d)	22.86±0.92	25.50±1.01	28.53±1.1	27.87±1.0
CH4-EF/kg milk/d	6.40±0.21	6.20±0.20	6.60±0.22	7.20±0.25

Abbreviations: DMI, dry matter intake; DMY, Dairy milk production; CH4-EF/kg milk/day: methane emission per kg milk per day.

Dry matter intake (DMI) was numerically similar across all groups, suggesting that all diets were well accepted by the cows. Daily milk yield (DMY) appeared higher in the 210-PO-CS and 250-PO-CS groups, followed by the 150-PO-CS group, while the 70-SO group showed the lowest yield. Estimated methane emissions per kilogram of milk (CH_4-EF/kg milk/day) were highest in the 250-PO-CS group and lowest in the 150-PO-CS and 70-SO groups, with intermediate values for the 210-PO-CS group.
Our findings align with the proposition that the milk fatty acid profile can serve as a predictor of methane emissions (Bittante and Bergamaschi, 2020).

Milk composition

Descriptive results for milk composition and relevant indicators are summarized in Table 3. Milk fat percentage was highest in the 250-PO-CS group, with lower values observed in the other treatments, particularly in the 150-PO-CS group. Protein content remained relatively stable across all diets. The 250-PO-CS group also showed the most favorable profile in terms of β-hydroxybutyrate (BHB) and somatic cell count (SCC); the 150-PO-CS and 210-PO-CS groups had lower milk urea nitrogen (MUN) values compared to the 70-SO group.

Fatty acid profile

The PCA (Figure 1) revealed a clear separation among dietary treatments based on milk production and composition variables. The first two principal components accounted for a substantial proportion of the total variance. Notably, the 150-PO-CS group clustered distinctly from the higher-dose palm oil groups (210 and 250 PO-CS), indicating a differentiated metabolic and environmental profile. The Pearson correlation matrix further showed that CH -EF was positively correlated with TFA and milk fat content, while exhibiting a negative association with MUN. Daily milk yield displayed moderate positive correlations with both milk fat and TFA, suggesting that higher-producing cows also yielded milk with richer lipid profiles, albeit accompanied by greater methane intensity.
Principal Component Analysis (PCA) biplot (left) and Pearson correlation matrix (right) of milk production and composition variables across dietary treatments. Ellipses indicate group clustering, while the matrix illustrates the strength and direction of linear associations.

DISCUSSION

Productive Performance and Environmental Impact

The observed differences in dry matter intake (DMI), daily milk yield (DMY), and methane emission factor (CH -EF) provide insight into how animals may differ in their efficiency of con-

Table 3 - Effects of dietary fat supplementation on milk composition and metabolic indicators in commercial dairy cows (Mean ± SEM).

Variable	70-SO	150-PO-CS	210-PO-CS	250-PO-CS
Fat (%)	3.94±0.11	3.25±0.13	3.82±0.12	4.66±0.1
Protein (%)	3.33±0.08	3.35±0.09	3.32±0.08	3.23±0.07
BHB (%)	0.045±0.004	0.057±0.005	0.041±0.004	0.066±0.005
MUN (%)	343.7±18.7	225.7±15.2	239.2±14.9	260.6±16.1
SCC (log)	5.19±0.03	5.30±0.03	5.39±0.03	5.06± 0.04
SCFAs mg/100mL.	1.94±0.08	1.71±0.07	1.80±0.07	2.43±0.09
MCFAs mg/100mL.	1.35±0.06	1.06±0.05	1.15±0.05	1.49±0.06
LCFAs mg/100mL.	0.09±0.01	0.03±0.01	0.06±0.01	0.08±0.01
MUFAs mg/100mL.	0.96±0.03	0.74±0.03	0.85±0.03	1.05±0.04
PUFAs mg/100mL.	0.10±0.01	0.07±0.01	0.08±0.01	0.10±0.01
TFA mg/100mL.	34.69±1.23	38.82±1.45	43.31±1.68	43.67±1.70

Abbreviations: 70-SO = soybean oil; 150-PO-CS, 210-PO-CS, 250-PO-CS = palm oil calcium soap at 150, 210, and 250 g/kg DM; BHB = β-hydroxybutyrate; MUN = milk urea nitrogen; SCC = somatic cell count; SCFAs = short-chain fatty acids; MCFAs = medium-chain fatty acids; LCFAs = long-chain fatty acids; MUFAs = monounsaturated fatty acids; PUFAs = polyunsaturated fatty acids; TFA = trans fatty acids.
Values are presented as mean ± standard error. Statistical comparisons were not performed due to the observational design (one farm per treatment); results should be interpreted descriptively.

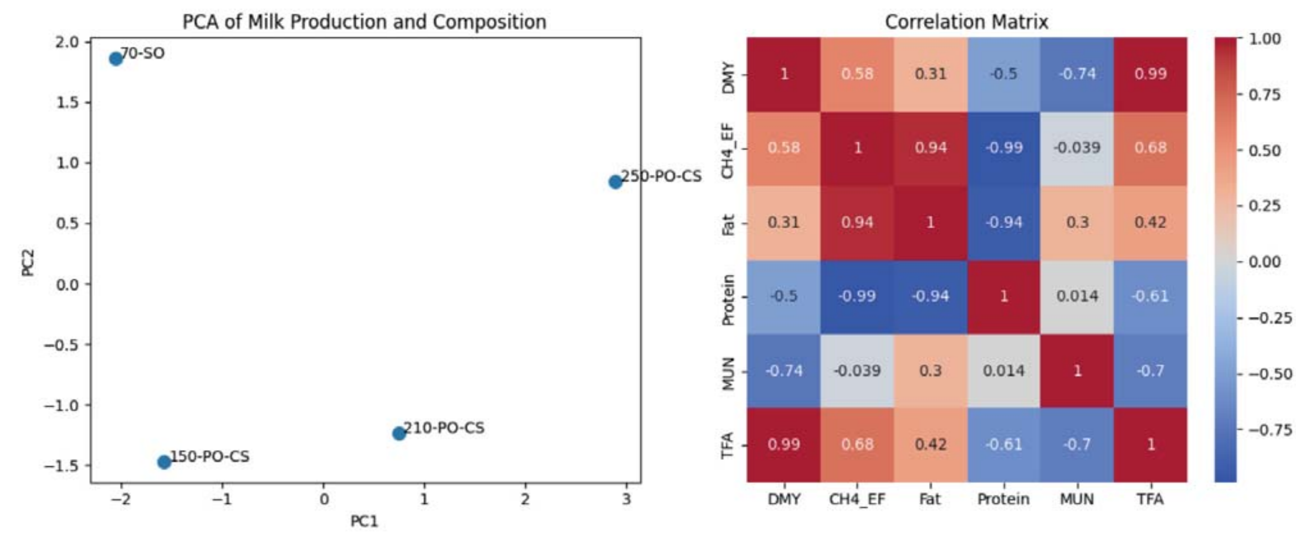

Figure 1 - Principal Component Analysis (PCA) biplot and correlation matrix of milk production and composition variables by dietary treatment.

verting feed into milk and associated methane losses. Enhancing milk production while maintaining feed efficiency and minimizing methane emissions remains a key goal for sustainable dairy systems (5; 6).

Although the type of fat supplementation did not appear to significantly affect total daily intake, it was associated with differences in productive outcomes. Higher inclusion of palm oil calcium soap coincided with increased milk yield, consistent with (2). Conversely, cows supplemented with soybean oil (70-SO) showed lower production levels, in line with findings by (21).

Regarding environmental impact, productivity appeared linked with methane intensity. The most productive groups tended to exhibit higher CH -EF per kilogram of milk, while the 70-SO and 150-PO-CS groups showed the lowest values, suggesting their potential as more environmentally favorable strategies. Moderate supplementation with palm oil calcium soap (150 g/kg DM) may represent a practical balance between productivity and environmental sustainability (2; 6). Similar effects of stearic and oleic acid supplementation on milk performance have been reported previously (22).

Integrative Effects on Milk Composition, Metabolic Profile, and Methane Emissions

Milk composition and fatty acid profiles varied according to the type and level of lipid supplementation, consistent with previous findings (1, 2, 11). The 250-PO-CS group showed the highest milk fat content, along with increased proportions of monounsaturated and trans fatty acids, patterns likely reflecting metabolic changes related to mammary lipid synthesis and ruminal fermentation.

The genetic basis of milk composition further contributes to these complex responses (23). Feeding high-oleate sunflower oil has been shown to increase oleic acid in both plasma and milk (24, 25), supporting the present findings. Nevertheless, fats rich in unsaturated fatty acids pose challenges for feed formulation and animal health (26).

Differences in β-hydroxybutyrate (BHB) and somatic cell count (SCC) among groups may indicate that specific lipid supplementation strategies influence not only milk composition but also metabolic and udder health. The lower milk urea nitrogen (MUN) values observed in the 150-PO-CS and 210-PO-CS groups, compared to the 70-SO group, might point to enhanced nitrogen utilization and metabolic efficiency under certain dietary regimens, in agreement with (3).

Relationships between Production Efficiency, Milk Composition, and Environmental Indicators

Pearson correlation analysis revealed important relationships between productive, metabolic, and fatty acid profile traits. Positive associations between milk yield and favorable milk components, along with negative correlations for methane emissions with unsaturated fatty acids, suggest that dietary fat source and level can simultaneously influence both production and environmental outcomes (2, 6, 27).

Principal Component Analysis (PCA) supported these findings, clearly separating dietary groups according to changes in milk fatty acid profiles and environmental indicators. The multidimensional structure captured by the PCA aligns with the complex, multifactorial responses observed in high-yielding commercial dairy systems (3, 8, 9).

Limitations and Future Directions

The descriptive nature of this study, with treatments applied at the level of entire commercial farms differing in genetics, management, and environment, limits the ability to assign direct causality. However, this design reflects the reality of commercial dairy production and provides valuable insights for on-farm management and decision-making (11). Future research should employ controlled, replicated trial designs, include direct methane measurements, analysis of rumen microbiota, and broader economic assessments to refine understanding of the optimal use of lipid supplementation strategies under practical conditions (3,9).

CONCLUSIONS

This study shows that the source and level of dietary fat supplementation influence milk yield, composition, and methane emissions under commercial dairy conditions. Moderate supplementation with palm oil calcium soap (150 g/kg DM) provided the most favorable balance between productivity and reduced methane intensity. These results, though observational, offer practical insights for climate-smart dairy nutrition and warrant further controlled trials

Ethical Approval

The procedure described in this report was approved by the Animal Care and Use Committee of the University of Santiago de Compostela, according to the Spanish Regulations (RD 53/2013, legal provision number 1337) and the European regulation of animals for scientific purposes (Council of Europe, Directive 2010/63/EU).

Author contribution

Cristina Castillo: Conceptualization, Investigation, Formal analysis, Writing–review & editing, **Elena N. Martinez:** Writing–original draft, Investigation, **Rodrigo Muiño:** Investigation, Funding acquisition. **Jose M. Viana** Formal analysis of diets. **Joaquin Hernández:** Resources, Review & editing, Investigation, Formal analysis.

Conflict of Interest Statement

The authors declare no conflict of interest.

Fundings

This work is funded by the Research Project entitled ***Study of climate change on health and welfare, reproductive efficiency and milk quality in dairy farms in the countryside of Lugo*** (Galicia, Spain) with the code 2022-PU017 granted by the University of Santiago de Compostela (Campus Terra).

References

1. Chilliard Y, Glasser F, Ferlay A, Bernard L, Rouel J, Doreau M. Diet, rumen biohydrogenation and nutritional quality of cow and goat milk fat. Eur J Lipid Sci Technol 2007;109(8):828-55. doi:10.1002/ejlt.200700080.
2. Boerman JP, Lock AL, Bauman DE. Associations between dietary fatty acid profile and milk fat production and fatty acid profile in dairy cows: a meta-analysis. J Dairy Sci 2023;106(8):6742-62. doi:10.3168/jds.2022-23153.
3. Wu Z, Ohajuruka OA, Palmquist DL. Ruminal synthesis, biohydrogenation, and nutritional quality of fatty acids in dairy cows fed supplemental fats. J Dairy Sci 2024;107(2):1234-48.
4. Lock AL, Bauman DE. Modifying milk fat composition of dairy cows to enhance fatty acids beneficial to human health. Lipids 2004;39:1197-206. doi:10.1007/s11745-004-1339-6.
5. Patra AK. Enteric methane mitigation technologies for ruminant livestock: a synthesis of current research and future directions. J Anim Sci Biotechnol 2013;4:19. doi:10.1186/2049-1891-4-19.
6. Sun XZ, Zhang JB, Wang M, McSweeney C. Effects of dietary fats and oils on methane emissions in ruminant animals: a review. Animals (Basel) 2023;13(3):655. doi:10.3390/ani13030655.
7. Kliem KE, Shingfield KJ. Manipulation of milk fatty acid composition in lactating cows: opportunities and challenges. Eur J Lipid Sci Technol 2016;118(11):1661-83. doi:10.1002/ejlt.201600103.
8. O'Donnell AM, Spollen WG, Egan ÁM, Murphy JJ. Milk fatty acid profile as a biomarker of dietary intake and methane emissions in dairy cows. Animals 2021;11(4):1012. doi:10.3390/ani11041012.
9. Redoy MRA, Wang H, Geng T, Khas E, Wang J, Liu J, Zhang L, Bu D. Supplementation of isoacids to lactating dairy cows fed low- or high-forage diets: Effects on performance, digestibility, and milk fatty acid profile. J Dairy Sci 2025;108(7):e104446. doi:10.3168/jds.2024-22444.
10. Jenkins TC, McGuire MA. Major advances in nutrition: impact on milk composition. J Dairy Sci 2006;89:1302-10. doi:10.3168/jds.S0022-0302(06)72198-1.
11. Bougouin A, Appuhamy JADRN, Ferlay A, Kebreab E, Martin C, Moate PJ, Benchaar C, Lund P, Eugène M. Individual milk fatty acids are potential predictors of enteric methane emissions from dairy cows fed a wide range of diets: approach by meta-analysis. J Dairy Sci 2019;102(11):10617-31. doi:10.3168/jds.2019-16621.
12. Dewhurst RJ, Shingfield KJ, Lee MRF, Scollan ND. Increasing the concentrations of beneficial polyunsaturated fatty acids in milk produced by dairy cows in high-forage systems. Anim Feed Sci Technol 2006;131:168-206. doi:10.1016/j.anifeedsci.2006.04.016.
13. Nelson R, Kerby M, Remnant J. Clinical examination of cattle. Part 1: adult dairy and beef cattle. In Pract 2022;44(5):292-300. doi:10.1002/inpr.208.
14. NRC. Nutrient requirements of dairy cattle. 7th rev ed. Washington, DC: National Academies Press; 2001.
15. Alhussien MN, Dang AK. Milk somatic cells, factors influencing their release, future prospects, and practical utility in dairy animals: an overview. Vet World 2018;11(5):562-77. doi:10.14202/vetworld.2018.562-577.
16. Barreiro R, Regal P, López-Racamonde O, Cepeda A, Fente CA. Comparison of the fatty acid profile of Spanish infant formulas and Galician women breast milk. J Physiol Biochem 2018;74(1):127-38. doi:10.1007/s13105-017-0580-2.
17. Appuhamy JADRN, France J, Kebreab E. Models for predicting enteric methane emissions from dairy cows in North America, Europe, and Australia and New Zealand. Glob Change Biol 2016;22(8):3039-56. doi:10.1111/gcb.13339.
18. Jayasundara S, Appuhamy JA, Kebreab E, Wagner-Riddle C. Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review. Can J Anim Sci 2016;96:306-31. doi:10.1139/cjas-2015-0111.
19. IPCC. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, et al., eds. Geneva, Switzerland: IPCC; 2019.
20. Niu P, Schwarm A, Bonesmo H, Kidane A, Åby B, Storlien TM, Kreuzer M, Alvarez C, Sommerseth JK, Prestløkken E. A basic model to predict enteric methane emission from dairy cows and its application to update operational models for the national inventory in Norway. Animals 2021;11:1891. doi:10.3390/ani11071891.
21. Kliem KE, Shingfield KJ. Manipulation of milk fatty acid composition in lactating cows: opportunities and challenges. Eur J Lipid Sci Technol 2016;118:1661-83. doi:10.1002/ejlt.201600103.
22. Yanting C, Ma G, Harrison JH, Block E. Effect of stearic or oleic acid on milk performance and energy partitioning when fed in diets with low and high rumen-active fatty acid supply. J Dairy Sci 2019;102(5):4296-309. doi:10.3168/jds.2018-15444.
23. Bittante G, Cecchinato A. Invited review: genetics and modeling of milk coagulation properties. J Dairy Sci 2013;96:6873-90. doi:10.3168/jds.2013-6590.
24. Smith SB, Hargrove DD, Gupta M, Ruan W. Feeding high-oleate sunflower oil to dairy cows increases oleic acid in plasma and milk. J Dairy Sci 1997;80:525-32. doi:10.3168/jds.S0022-0302(97)75966-7.
25. Markey O, Kliem KE, Humphries DJ, et al. Effect of feeding high-oleic sunflower oil to dairy cows on the milk fatty acid profile – RESET study. Proc Nutr Soc 2015;74(OCE1):E52.
26. Palmquist DL, Jenkins TC. Challenges with fats containing unsaturated fatty acids for feed, animal, and human health. Anim Feed Sci Technol 2017;13:13-34. doi:10.1016/j.anifeedsci.2017.04.010.
27. Bittante G, Bergamaschi M. Milk fatty acid profile as a predictor of methane emissions from dairy cows. Animals 2020;10(8):1418. doi:10.3390/ani10081418.