Seasonal, parity, and lactation stage effects on daily methane emissions in dairy cattle in Taiwan

P.-An Tu[1], Yi-Hsuan Chen[1], Yi-Hsin Yeh[1], Yueh-Tung Chen[1], Jeng-Fang Huang[2] and Jen-Wen Shiau[1]

[1]Northern Region Branch, Taiwan Livestock Research Institute, MOA. No. 207-5, Pitoumian, Xihu Township, Miaoli County 368003, Taiwan
[2]Taiwan Livestock Research Institute, MOA. No. 112, Farm Road, Hsinhua, Tainan, Taiwan
Corresponding Author: tpa@mail.tlri.gov.tw

Abstract

This study analyzed daily methane emissions (dCH4) in Taiwanese dairy cows across 199 commercial farms, using 123,397 records. A mid-infrared spectroscopy (MIR)-based approach to predict milk fatty acid profiles, integrated with energy-corrected milk yield (ECM), was applied to estimate CH4 emissions. We examined parity, lactation stage, and seasonal variation. Emissions rose significantly with parity (432.99 ± 0.45 g/d in first-parity vs. 469.16 ± 0.70 g/d in cows of third parity or greater; $p < 0.0001$). Early lactation yielded the highest emissions (517.08 ± 1.14 g/d in month 1), gradually declining to a minimum at month 9 (426.47 ± 1.10 g/d) before rebounding slightly toward month 12 (401.56 ± 1.59 g/d). These findings align with the high nutrient demands and negative energy balance in early lactation and potential body reserve replenishment in late lactation. Seasonal analysis showed elevated emissions in winter (December-March, 450–472 g/d) compared with summer (July–September, 418–439 g/d). This pattern likely reflects greater fibrous feed intake and longer rumen retention in cooler months, versus heat stress–related drops in dry matter intake during hot periods. These results demonstrate how parity, lactation dynamics, and seasonal conditions all influence CH4 output, highlighting opportunities for targeted mitigation. By routinely collecting on-farm data, the prediction equation helps producers identify high-emission cohorts and periods, guiding management strategies such as diet adjustments or feed additives. Future work should examine interactions between cow-level factors and farm practices to refine models, enhance scalability, and support climate-smart dairy production.

Keywords: Methane emission, season, parity, lactation stage.

Introduction

The dairy industry plays a significant role in global greenhouse gas emissions, with methane (CH_4) from enteric fermentation being a substantial contributor. Approximately 17% of global methane emissions are attributed to enteric fermentation from livestock, with dairy cows specifically contributing about 3.3% to overall anthropogenic greenhouse gas emissions (Lyons *et al.,* 2018). This highlights the urgent need for effective management and mitigation strategies tailored to dairy production systems, especially in regions with high dairy activity, such as Taiwan. Recent studies indicate that various factors influence methane emissions, including cow genetics, diet composition, and management practices, providing multiple avenues for improvement (Difford *et al.,* 2018; Bittante *et al.,* 2018).

Research has shown that dietary factors significantly impact enteric methane emissions. For instance, the nutritional profile of feeds influences rumen fermentation dynamics, which in turn affects methane output. High-fiber diets generally produce more methane compared to higher-concentrate diets, necessitating careful dietary formulations to balance productivity with environmental sustainability (Moate *et al.,* 2017). Furthermore, certain feed additives and supplements have demonstrated potential in mitigating methane production by altering microbial populations in the rumen (Zhou *et al.,* 2011; Enríquez-Hidalgo *et al.,* 2020). The lactation stage of cows also plays a critical role; emissions typically peak during early lactation, aligning with increased nutrient demands and negative energy balances during this period (Bittante *et al.,* 2018).

This study aims to analyze daily methane emissions from Taiwanese dairy cows across a substantial cohort of 199 commercial farms, utilizing advancements in analytical techniques such as mid-infrared spectroscopy (MIR). This approach not only facilitates the prediction of milk fatty acid profiles but also integrates energy-corrected milk yields (ECM) to enhance the accuracy of methane emissions estimation. As suggested by previous research, factors such as parity and seasonal variations are expected to correlate significantly with methane outputs. Increases in emissions related to parity are linked to physiological changes occurring with repeated pregnancies and lactation cycles, while seasonal changes reflect variations in feed intake and digestion efficiency influenced by environmental conditions (Grešáková *et al.,* 2021; Boré *et al.,* 2022).

This study aims to characterize methane emissions associated with different parity numbers and lactation stages while exploring seasonal variations that could indicate broader environmental impacts of dairy operations. The results are anticipated to provide insights into targeted mitigation strategies that can be implemented on farms to address climate change while maintaining economic viability in dairy production. By routinely collecting and analyzing on-farm data, the developed predictive models can assist producers in managing their herds to reduce emissions while enhancing overall productivity and sustainability within the dairy sector (Donadia *et al.,* 2023; Ramin *et al.,* 2023).

Materials and methods

Study location and design

The study was conducted on 199 commercial dairy farms located in Taiwan, aiming to analyze daily methane emissions (dCH_4) from dairy cows. A total of 123,397 records were collected throughout the study duration, encompassing a wide range of cow varieties, management practices, and environmental conditions.

Data collection

Milk Sampling: Milk was collected from participating dairy farms under standardized conditions. Samples were transported and processed according to established protocols to maintain sample integrity for subsequent analysis.

Mid-infrared spectroscopy measurement

The quantification of methane emissions was performed using mid-infrared spectroscopy (MIR). The following parameters were systematically evaluated to derive methane output estimates:

- Milk Yield: Daily energy-corrected milk yield (ECM) was recorded for each cow. ECM is crucial as it serves as an indicator of the cow's productivity and nutritional intake.
- Fatty Acid Composition: The MIR analysis focused on the identification and quantification of specific milk fatty acids, including:
- Saturated fatty acids (SFAs)
- Unsaturated fatty acids (UFAs)

  Trans fatty acids (TFAs)

Calculation of methane emissions

The methane emissions were calculated based on the MIR-derived fatty acid profiles and the corresponding ECM. The methodology employed was established from the predictive model detailed in Engelke *et al* (2018), facilitating the estimation of dCH_4 based on the compositions of fatty acids.

Statistical analysis

Statistical comparisons of methane emissions were conducted based on the following factors:

1. Parity: Cows were categorized according to their parity status (first, second, and third parity or greater) to assess differences in emissions linked to reproductive history.
2. Lactation Stage: The lactation period was classified into early, mid, and late stages, acknowledging the variations in energy demands throughout the lactation cycle.
3. Seasonal Variation: The dataset was analyzed across different seasons, specifying periods such as winter (December–March) and summer (July–September), to evaluate the impact of climatic conditions on methane emissions.

Statistical analyses were performed using appropriate software to determine the influence of each factor on daily methane emissions. Analysis of Variance (ANOVA) was employed to evaluate differences in mean methane emissions across the different parities and lactation stages, with post-hoc tests utilized where necessary to identify specific group differences. Moreover, seasonal variances in methane emissions were assessed using multiple comparison tests to provide a comprehensive overview of environmental impact on methane production. A significance level of $P < 0.05$ was adopted for all statistical comparisons.

Results

Results from this study reveal significant variations in daily methane emissions (dCH_4) among Taiwanese dairy cows across various factors such as parity, lactation stage, and seasonal influences. Our analysis, which encompassed 123,397 records from 199 commercial farms, provides the following key findings:

Influence of parity

Methane emissions were significantly affected by parity (Fig. 1). Cows with first parity emitted an average of 432.99 ± 0.45 g/d, while those with third parity or greater recorded emissions of 469.16 ± 0.70 g/d, demonstrating a statistically significant increase (P<0.0001) associated with repeat lactation cycles.

Lactation stage variability

Emissions peaked during early lactation, where the highest recorded emission was 517.08 ± 1.14 g/d in the first month (Fig. 2). A gradual decline was observed, with emissions dropping to 426.47 ± 1.10 g/d by the ninth month of lactation, before slightly increasing to 401.56 ± 1.59 g/d towards the twelfth month. This trend correlates with the high nutrient demands of early lactation and the potential body reserve replenishment during the later stages.

Seasonal variations

Seasonal analysis indicated higher methane emissions during the winter months (December to March) ranging between 450 and 472 g/d compared to the summer months (July to September), where emissions were observed to be between 418 and 439 g/d (Fig. 3). The increased emissions in winter can likely be attributed to higher fibrous feed intake and longer rumen retention times associated with cooler temperatures, while summer saw reduced emissions possibly due to heat stress affecting dry matter intake.

These findings underscore the importance of parity, lactation dynamics, and seasonal conditions as crucial factors influencing methane output in dairy cows, thereby demonstrating potential pathways for targeted mitigation strategies that can be readily implemented on commercial dairy farms.

Discussion

This study assessed daily methane emissions (dCH) from dairy cows across 199 commercial farms in Taiwan, implementing a mid-infrared spectroscopy (MIR) based method to predict emissions reliably. The results indicated that various physiological and environmental factors, including parity, lactation stage, and seasonal variation, significantly influenced methane emissions, aligning with existing literature that emphasizes these relationships in dairy cattle.

The analysis revealed that methane emissions increased notably with parity, with higher emissions observed in cows of third parity or greater (469.16 ± 0.70 g/d) compared to first-parity cows (432.99 ± 0.45 g/d). This finding aligns with previous research suggesting a correlation between increased physiological demands and methane production due to higher energy intake and subsequently altered fermentation patterns in the rumen as cows age (Takizawa *et al.,* 2023; Loza *et al.,* 2023). Furthermore, the peak methane emissions during early lactation (517.08 ± 1.14 g/d in the first month) can be attributed to the cow's heightened nutrient requirements during this critical period, which is well-supported by studies indicating that energy deficits and nutritional stress can amplify methane production due to the complex interactions of rumen fermentation and fatty acid metabolism (Loza *et al.,* 2023; Bittante and Bergamaschi, 2019).

Our seasonal analysis found that winter emissions were significantly higher than those in summer, likely due to increased fibrous feed intake and extended rumen retention times when temperatures dropped (Bougouin *et al.,* 2019). This pattern highlights the

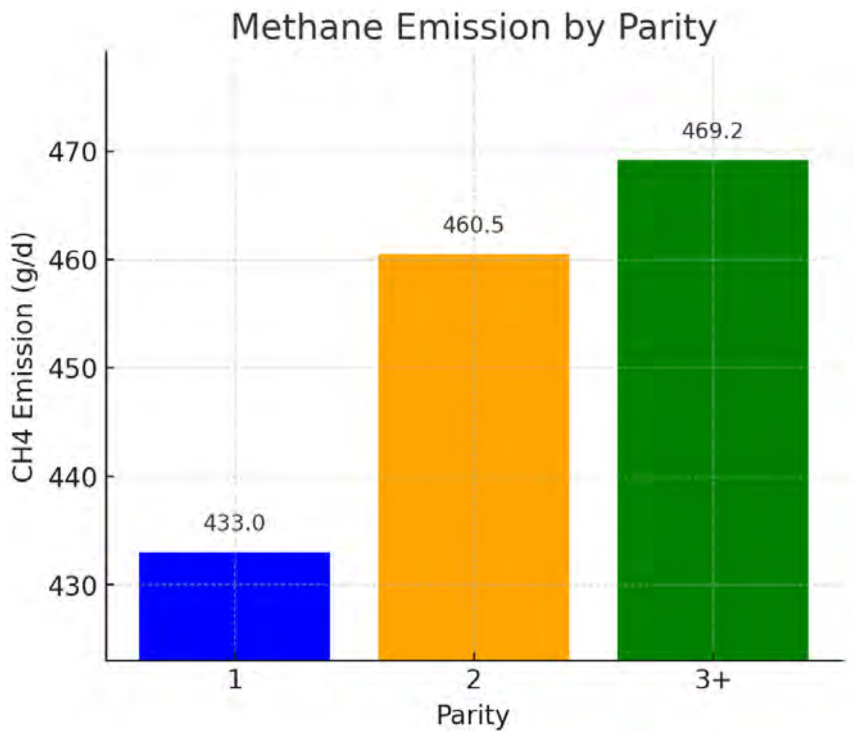

Figure 1. Methane Emissions by Parity. Bar chart compares methane emissions (CH_4 g/d) among cows of different parities. First-parity cows exhibit the lowest emissions, while emissions increase with parity, with cows of three or more parities showing the highest methane production.

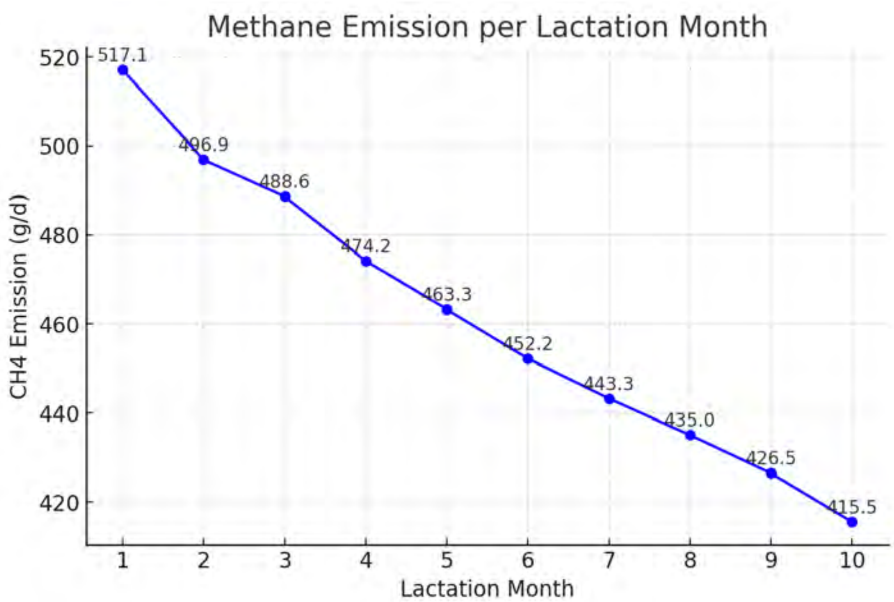

Figure 2. Methane Emissions Across Lactation Months. Blue line presents methane emissions (CH_4 g/d) throughout the lactation period (1-12 months). The results indicate a gradual decline in emissions as lactation progresses, with the highest emissions at the start of lactation and the lowest emissions toward the later months.

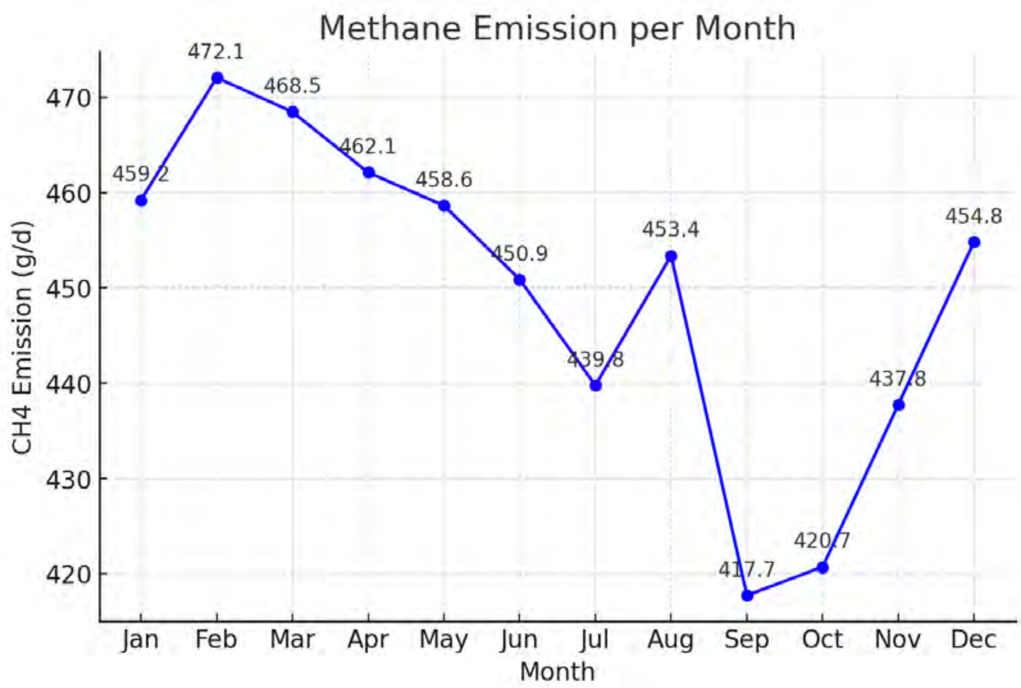

Figure 3. Monthly Methane Emissions in Dairy Cows. Blue line illustrates the variation in methane emissions (CH_4 g/d) across different months of the year. The highest emissions are observed in February, while the lowest emissions occur in September, suggesting potential seasonal influences on methane production.

effects of dietary composition and environmental conditions, reinforcing findings that suggest nutritional strategies can mitigate methane emissions effectively when adjusted seasonally to optimize dairy cow performance (Ho *et al.,* 2019).

Moreover, the use of MIR to assess milk fatty acid profiles proved effective for estimating methane emissions, consistent with findings that indicate fatty acid composition in milk as a predictive indicator of enteric methane production (Bittante and Bergamaschi, 2019; Timlin *et al.,* 2024). This study effectively utilized the correlations established in previous studies demonstrating how changes in milk fatty acid profiles can reveal underlying metabolic processes linked to rumen fermentation and methane emissions (Bittante and Bergamaschi, 2019). The significant relationship between fatty acid profiles and methane production reaffirms the potential for MIR not only as a diagnostic tool but also as a practical approach to improve farm management and reduce greenhouse gas emissions.

Future research should focus on refining these predictive models, considering additional factors such as specific dietary components and herd management practices, to enhance the robustness of methane emission estimates. Interactions between cow-level factors, including genetics and metabolic profiles, could also be explored further to develop more precise dairy management strategies aimed at achieving climate-smart production (Loza *et al.,* 2023; Ho *et al.,* 2019).

Conclusion

This study highlights the complex interplay between parity, lactation dynamics, and seasonal variations in influencing methane emissions in dairy cows, underscoring the importance of targeted dietary and management strategies to mitigate emissions effectively. By leveraging MIR techniques for estimating milk fatty acid profiles, dairy producers can gain valuable insights into emissions profiles, enabling them to implement interventions that support both environmental sustainability and productivity.

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