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RESEARCH ARTICLE

Measurement of seasonal variations in methane and carbon dioxide emissions from dairy manure management under warm climate conditions

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ABSTRACT

Dairy manure management is a major contributor to greenhouse gases (GHG), and its quantification under warm climatic conditions is essential for improving mitigation strategies and emission inventories. The GHG emissions, including methane (CH_4) and carbon dioxide (CO_2), were quantified in a free-stall dairy farm housing 1300 lactating cows under warm-climate conditions in İzmir, Türkiye. In situ measurements were conducted over a 1 yr period using the flux chamber method across five emission source areas (ESA): Barn floor, paddock, slurry manure storage (SMS), solid manure pile (SMP), and liquid manure lagoon (LML). The data were analyzed using one-way ANOVA and Tukey's HSD test to evaluate seasonal variations ($p < 0.05$). The highest CH_4 flux in SMP in summer (210 μmol m^{-2} s^{-1}) was 5.1 times higher than winter. The CH_4 flux in LML in summer (36.35 μmol m^{-2} s^{-1}) was 4.8 times higher than winter. In SMS, the highest CH_4 flux occurred in autumn (38 μmol m^{-2} s^{-1}), which was 5.9 times higher than spring. The highest CO_2 flux was 1126 μmol m^{-2} s^{-1} in SMP in summer. The annual contribution of LML (31.3 t CH_4 yr^{-1}) in all ESA is 61.85%. The farms annual emission factors for CH_4 (EF_{CH4}) and CO_2 (EF_{CO2}) are 39.59 and 979.11 kg hd^{-1} yr^{-1}, respectively. The highest EF_{CH4} is 0.117 kg CH_4 hd^{-1} d^{-1} during summer in LML. Additionally, it is understood that the combination of rubber mats and scraper systems may comparatively reduce in-barn CH_4 formation relative to barns where other bedding materials are used. These results indicate that, particularly in dairy farms located in warm climate regions such as Türkiye, high emissions occur from liquid manure stored in open-air conditions at high temperatures and development of liquid manure management strategies priority for emission mitigation.

Key words: Dairy cattle, greenhouse gas, lagoon, livestock waste, manure management, mitigation.

INTRODUCTION

Livestock production systems are recognized as major contributors to global greenhouse gas (GHG) emissions, particularly CH_4 and nitrous oxide (N_2O), which possess 28 and 265 times higher global warming potentials than CO_2, respectively. Manure management alone accounts for approximately 5%-10% of global agricultural GHG emissions (Ussiri and Lal, 2017) and up to 37% of global CH_4 emissions (IPCC, 2019). Dairy farming, in particular, contributes substantially to these emissions through the large amounts of manure generated and the predominance of housing and storage systems that promote anaerobic microbial decomposition (IPCC, 2019). The growing herd sizes in commercial dairy operations have intensified the use of liquid, slurry, and lagoon-based systems, which are known to emit high levels of CH_4 under anaerobic and warm conditions. These emissions are further amplified by seasonal temperature fluctuations that alter microbial activity and redox conditions, thereby influencing both CH_4 and CO_2 fluxes throughout the year (Won et al., 2020; Chachei, 2024).

Despite the global importance of livestock emissions, most available studies have been conducted under cold or temperate climates, on small-scale farms, or at the laboratory scale, which may not accurately represent the dynamic emission processes in warm regions. Measurement data from large-scale dairy farms in Mediterranean-type climates remain extremely scarce, particularly those assessing emissions at specific emission source areas (ESA) such as barn floors, paddocks, lagoons, and manure storage units (Borhan et al., 2011; Fuertes et al., 2023). The Institut National de la Recherche Agronomique (INRA)-Agence de l’Environnement et de la Maîtrise de l’Énergie (ADEME) (Hassouna et al., 2016) and Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019) guidelines emphasize that CH_4 generation increases exponentially under warm conditions and recommend ESA-based field measurements to capture spatial and temporal variability. However, no comprehensive field-based study has yet been conducted in Türkiye, where dairy production is concentrated in warm Mediterranean basins that are highly vulnerable to climate-driven increases in emissions.

This study aims to quantify CH_4 and CO_2 emissions from emission source areas (ESAs) over a full annual cycle at a commercial dairy farm located in the warm Mediterranean region of Türkiye. By correlating seasonal temperature dynamics with emissions, this research provides a field-based dataset for warm climate dairy farm systems in Türkiye, offering new insights into emission variability and providing essential data for developing region-specific mitigation strategies for manure management.

MATERIALS AND METHODS

Site description

This study was conducted at a dairy farm in İzmir-Tire region (38°07'28" N, 27°39'43" E; 65 m a.s.l.) where dairy farming is intensive in Türkiye. Tire is characterized by a typical hot Mediterranean climate. Summers are generally hot and dry, with maximum temperatures reaching up to 37 °C, while the mean annual temperature is approximately 17-18 °C.

The dairy had 1300 lactating cows and 8 free-stall barns with rubber mats. Each dairy barn is designed in the same way in terms of size, manure management method and number of animals housed. The dairy cattle breed (Holstein) raised in each dairy barn is homogeneous in terms of average body weight (± 500 kg) and feed ration. Based on this information, it is expected that the structure of the manure and the amount of emissions formed in each dairy barn will be similar. Emission measurements were carried out in a sample dairy barn selected to represent all dairy barns in the farm, since all dairy barns have the same structural, administrative and manure structure characteristics.

The slurry manure on service lanes in the barns is collected seven times a day using scrapers and transported via pipes to an underground concrete slurry manure storage (SMS). The manure stored in the SMS is separated into liquid and solid forms using a screw press solid separator. The liquid manure is stored in liquid manure lagoon (LML), while the solid manure is stored in a solid manure pile (SMP) on a concrete floor.

In this study flux measurements were conducted on barn floors (manure scraper alley), walking areas (paddocks), SMS, LML, and SMP defined as emission source areas (ESA) by Borhan et al. (2011) and IPCC (2019). However, emissions from enteric fermentation, respiration, and machinery were not included in the study. The location of the dairy farm and position of ESA are shown in Figure 1.

Figure 1. Location of the dairy farm and emission source areas where emission measurements were conducted. 1. Barn. 2. Paddock. 3. Slurry manure storage. 4. Solid manure pile. 5. Liquid manure lagoon.

CH_4 and CO_2 flux measurement system and procedure

The CH_4 and CO_2 fluxes were measured with LI-7810 CO_2 and CH_4 trace gas analyzer coupled with an 8200-01S Smart Chamber (LI-COR Biosciences, Lincoln, Nebraska, USA) that operates according to the flux chamber-based greenhouse gas flux measurement system proposed by Institut National de la Recherche Agronomique (INRA)-Agence de l'Environnement et de la Maîtrise de l'Énergie (ADAME) (Hassouna et al., 2016). Measurements were conducted over a 1 yr period to quantify total emissions, estimate seasonal emission trends, and identify critical ESA for targeted mitigation efforts.

The analyzer continuously measured CH_4 and CO_2 concentrations at nmol m^{-2} s^{-1} and µmol m^{-2} s^{-1} levels respectively. Fluxes of these gases (expressed in nmol m^{-2} s^{-1} or µmol m^{-2} s^{-1}) were automatically calculated in real time by the SoilFluxPro software (LI-COR) based on the rate of increase in gas concentration (dC/dt) inside the chamber. The software automatically selects the most appropriate regression model—linear or exponential—depending on whether the concentration increases linearly or nonlinearly over time, and applies the model with the highest coefficient of determination (R^2) to enhance the accuracy of emission estimation (Leytem et al., 2024).

The measurements were carried out over a 1 yr period (5 January 2023-24 December 2023), approximately every 15 d. Daily measurements were taken between 11:00 and 15:00 h, corresponding to the period of peak emission activity, with an average of 10 replicates per measurement (Cárdenas et al., 2021). In total, 1369 flux data points with low variance and high coefficients of determination (R^2) across the different ESA were evaluated (Table 1).

Table 1. Number of measurement points, measurement days and evaluated measurements in the emission source areas (ESA) of the farm.

		ESA	Number of measurement points	Number of measurement day	Number of evaluated measurements
Housing areas	1	Barn (Manure scraper alley)	3	24	365
	2	Paddock	3	24	374
Manure storage areas	3	Slurry manure storage	1	24	199
	4	Liquid manure lagoon	1	24	171
	5	Solid manure pile	1	24	260
Total					1369

The Smart Flux Chamber (volume of 4244.1 cm^3, covers areas of 317.8 cm^2 and air mixing inside the chamber is achieved by a standard 250 cm^3 min^{-1} air flow produced by the analyzer) was positioned over each ESA to collect gases samples. The gas samples were pipe into the LI-7810 trace gas analyzer to determine CH_4 and CO_2 concentrations as volume mixing ratios. The analyzer operates based on optical feedback cavity-enhanced absorption spectroscopy (OF-CEAS) at a measurement frequency of 1 Hz. The instrument precision under ambient conditions was 0.6 nmol mol^{-1} for CH_4 (at 2 µmol mol^{-1}) and 3.5 µmol mol^{-1} for CO_2 (at 400 µmol mol^{-1}) (Johannesson et al., 2024). The overall configuration of the smart trace gas analyzer system used in this study is shown in Figure 2. Unlike conventional chamber methods (such as U.S. EPA Method TO-14A, which involve collecting gas samples in canisters and subsequently analyzing them in a laboratory by gas chromatography) this portable and integrated system enables on-site, real-time analysis of gas samples (Zaman et al., 2021). This is one of the most frequently used methods for measuring gas fluxes from various environments such as landfills, soils, and volcanic areas, and it has been widely described in the scientific literature (Jassal et al., 2016). The same method has also been applied to livestock manure management systems, including solid dairy cattle manure, digestate storage, liquid manure storage lagoons, settling basins, loafing pens, barn floors, and manure lanes, as well as liquid dairy cattle manure (Borhan et al., 2011; Vergote et al., 2020; Cárdenas et al., 2021). Overall, this approach provides a practical, reliable, and non-destructive technique for quantifying greenhouse gas (GHG) emissions from livestock manure sources (Borhan et al., 2011).

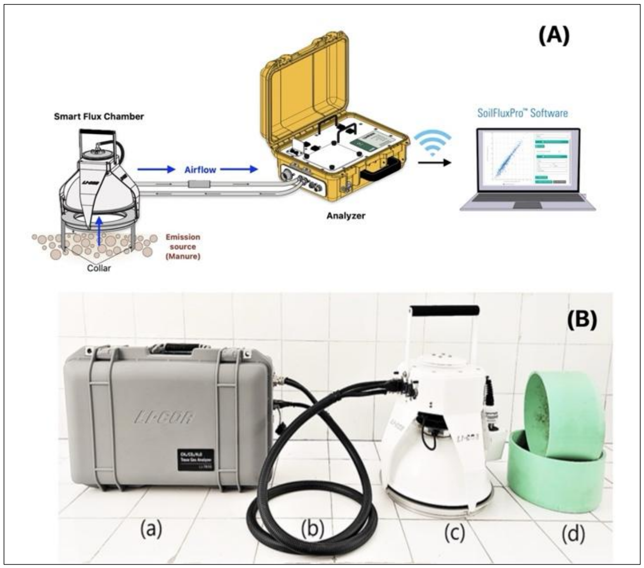

Figure 2. A) Schematic flow diagram of Smart Trace Gas Analyzer system. B) Components of Trace Gas Analyzer: Trace Gas Analyzer (a), data transmission cable and gas transmission pipe (b), smart flux chamber (c), collar (d).

In this study flux measurements were conducted on five different ESA. In the housing areas were conducted in a representative barn, with a total of six measurement points, three located along the barn floor (manure scraper alley) inside the barn and three in the paddock area. Each measurement point was sampled ten times on average, and measurements were performed at sites where the manure distribution on the ground was visually homogeneous (Borhan et al., 2011).

The SMP was temporarily stored for only a short period per day, as it was frequently separated and transported to biogas facilities or used directly in crop production. Consequently, no large manure piles accumulated on the farm. Emission measurements for the SMP were therefore conducted from a single representative point (midpoint) of the small remaining pile (Figure 3). In contrast to the short-term storage of solid manure, liquid manure is stored for extended periods (on average 4-6 mo) due to its seasonal limitations in agricultural use. During sampling, mechanical mixers were operating, which ensured horizontal and vertical homogeneity in the fully mixed LML and SMS, preventing stratification. On the measurement day, liquid and slurry manure samples were randomly collected, transferred into standardized 40 L containers, and flux measurements were immediately performed on the manure surface under the same atmospheric conditions as the storage facilities.

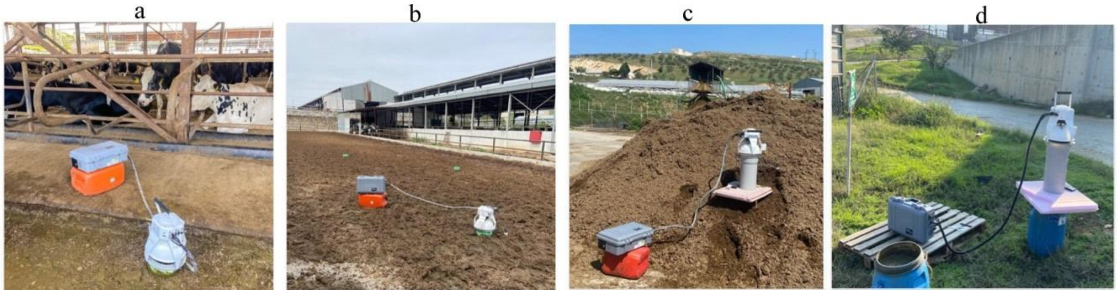

Figure 3. Emission measurement points in emission source areas (ESA): Barn (a), paddock (b), solid manure pile (c), slurry and liquid manure (d).

Estimation of CH_4 and CO_2 emissions

Based on the instantaneous CH_4 and CO_2 fluxes measured at each ESA, the methods used to estimate daily, seasonal, and annual total emissions and emission factors (EFs) are described below.

Conversion of instantaneous CH_4 and CO_2 fluxes to daily mass emission fluxes. For each ESA, the instantaneous CH_4 and CO_2 gas fluxes (µmol m^{-2} s^{-1}) obtained using the closed chamber method were converted to daily mass emission fluxes (kg m^{-2} d^{-1}) by considering the molar mass of each gas (16.04 for CH_4 and 44.01 for CO_2) and their respective molecular weight conversion factors (Borhan et al., 2011; Courtois et al., 2019; IPCC, 2019; Venterea et al., 2020).

Calculation of daily total emissions. For each ESA, the daily total emissions (kg d^{-1}) were calculated by multiplying the daily mass emission fluxes by the corresponding surface area (m^2) of the ESA and the fraction of the surface covered with manure (Rm) (Borhan et al., 2011; dos Reis and Ribeiro, 2019; IPCC, 2019). In the paddock and barn floor areas, the Rm value was determined visually on each measurement day and averaged approximately 20%. This proportion was used as an areal correction factor to account for the representativeness of the measured fluxes within each emission source area (Hristov et al., 2013). Accordingly, the areal correction was applied only to the emission values calculated for the manure-covered portions of the surface observed during the measurements. For manure storage areas (solid, liquid, and slurry), the entire surface area of the storage was considered manure-covered (Rm = 1); thus, the total daily emissions were calculated directly using the full storage surface area (Borhan et al., 2011; dos Reis and Ribeiro, 2019; IPCC, 2019).

Estimation of seasonal and annualized total emissions. First, the daily emission values (kg d^{-1}) for the days between consecutive measurement intervals (approximately every 15 d) were estimated using linear interpolation, assuming a linear change in emissions between two measurement dates. Then, for each ESA, the seasonal (kg d^{-1}) and annual total emissions (kg yr^{-1}) were obtained by temporal integration of the daily emissions over 365 d using the trapezoidal integration method. This approach is widely used in environmental measurement studies to reduce the uncertainty caused by seasonal variability and data gaps (IPCC, 2019).

Estimate of seasonal and annualized emissions factors. The seasonal (kg hd^{-1} d^{-1}) and annual (kg hd^{-1} yr^{-1}) emission factors ($EFCH_4$ and $EFCO_2$) were calculated by dividing the corresponding seasonal and annual total emissions by the total number of lactating dairy cows on the farm (1300 head). This farm-specific, measurement-based approach is consistent with the Tier 3 framework defined in the IPCC (2019) Refinement guidelines.

Statistical analysis

Seasonal variations of CH_4 and CO_2 emissions were analyzed using one-way ANOVA followed by Tukey's HSD test ($p < 0.05$). In this context, mean values between groups were compared, and standard deviations were taken into account to determine significant differences. Additionally, Pearson's correlation analysis was conducted to evaluate the relationship between air temperature and gas emissions. All statistical analyses were performed using the SPSS v30 software package (IBM, Armonk, New York, USA) (Won et al., 2020).

RESULTS

CH_4 flux and seasonal variation

Daily average CH_4 emissions in ESA reached their highest levels during summer when air temperatures exceeded 37 °C. The maximum values were recorded as 416 µmol m^{-2} s^{-1} in the SMP on 30 August 2023; 55 µmol m^{-2} s^{-1} in the LML during summer (9 August 2023); and 83 µmol m^{-2} s^{-1} in autumn (24 October 2023). In the SMS the highest emission was 64 µmol m^{-2} s^{-1} during autumn (16 September 2023). In contrast, emissions in the paddock and barn were lower (Figure 4).

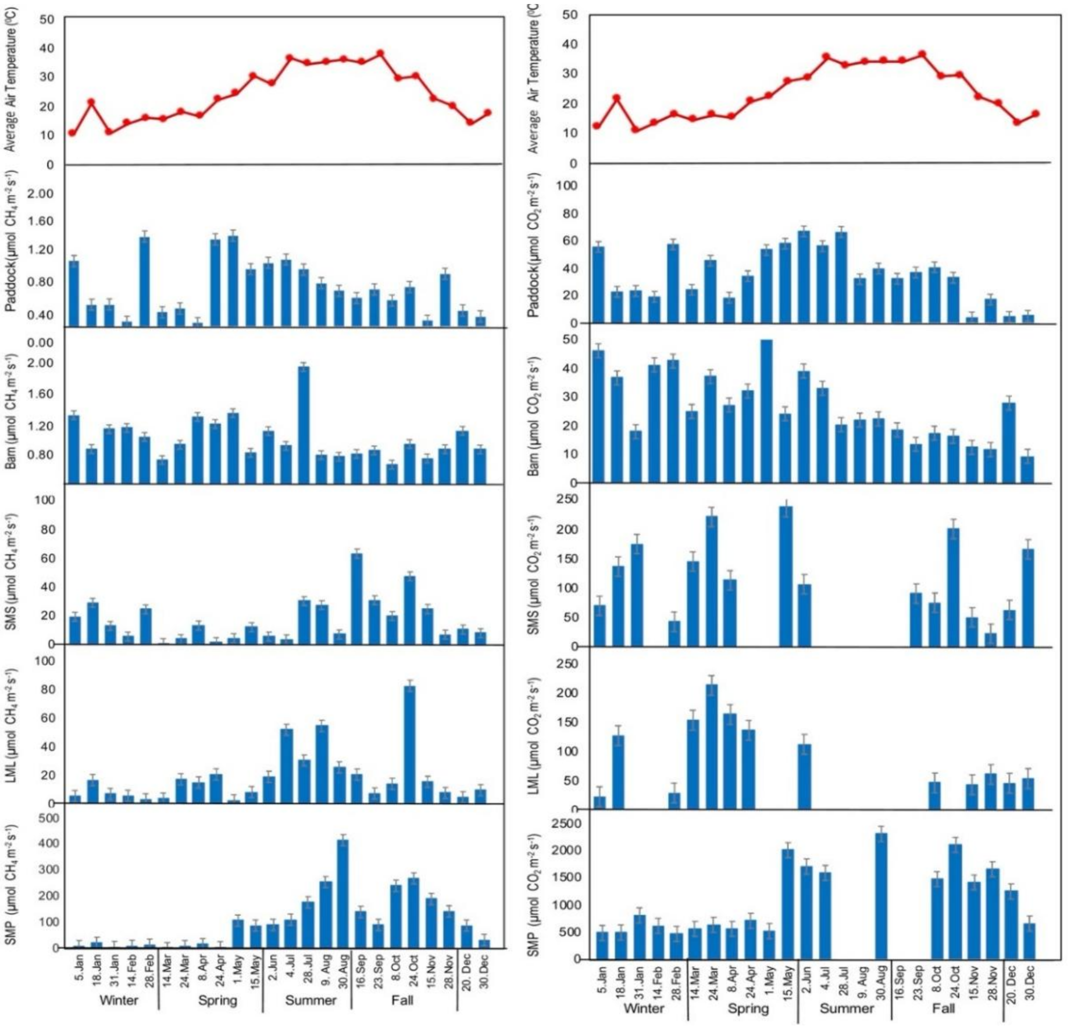

Figure 4. Variation of CH_4 and CO_2 flux during the year in each emission source areas. Error bars indicate the standard deviation. SMS: Slurry manure storage; LML: liquid manure lagoon; SMP: solid manure pile.

Seasonal averages of CH_4 and CO_2 fluxes in the ESA are presented in Table 2. In the SMP and LML, daily average CH_4 emissions significantly increased during summer due to rising temperatures. ANOVA analysis revealed significant seasonal differences in CH_4 emissions in the SMP, LML, and SMS ($p < 0.05$). Summer averages in the SMP were 5.1 times higher than in winter, LML averages were 4.8 times higher, and SMS autumn averages were 5.9 times higher than in spring. Tukey HSD tests confirmed these differences, but seasonal changes in barns and paddocks were insignificant ($p > 0.05$).

Pearson correlation analysis showed a significant positive correlation between temperature increases and CH_4 emissions in the SMP ($r = 0.729$, $p < 0.01$) and LML ($r = 0.670$, $p < 0.01$). However, nonsignificant correlation was observed in the SMS, barns or paddocks (Table 3). These results identify the SMP and LML as the most critical ESA on the farm. Their exposure to atmospheric conditions enhances microbial activity in manure, particularly at high temperatures, leading to elevated emissions.

Table 2. Seasonal variation of measured CH_4 and CO_2 fluxes (average ± standard deviation) in emission source areas (ESA). Averages of by the same lower-case letter in rows for a particular location are not significantly different ($p > 0.05$). SMS: Slurry manure storage; LML: liquid manure lagoon; SMP: solid manure pile.

	CH_4 Flux (µmol m^{-2} s^{-1})			
ESA	Winter	Spring	Summer	Fall
Paddock	0.5 ± 0.4^{a}	0.7 ± 0.5^{a}	0.8 ± 0.1^{a}	0.4 ± 0.1^{a}
Barn	0.7 ± 0.2^{a}	0.7 ± 0.2^{a}	0.8 ± 0.5^{a}	0.4 ± 0.1^{a}
SMS	15.0 ± 8.7^{b}	6.3 ± 4.8^{a}	15.0 ± 13.0^{b}	38.0 ± 18.0^{b}
LML	8.0 ± 4.2^{b}	11.3 ± 6.8^{ab}	36.4 ± 16.0^{a}	28.0 ± 31.0^{ab}
SMP	41.0 ± 49^{b}	38.0 ± 43.0^{b}	210.0 ± 132.0^{a}	186.0 ± 73.0^{ab}
	CO_2 Flux (µmol m^{-2} s^{-1})			
Paddock	31.0 ± 48.0	39.3 ± 27.0	52.1 ± 40.3	29.0 ± 23.3
Barn	31.0 ± 20.0	30.0 ± 17.0	26.1 ± 12.4	15.4 ± 7.0
SMS	129.3 ± 58.0	167.0 ± 67.3	107.2 ± 20.1	95.0 ± 81.0
LML	52.3 ± 34.0	173.0 ± 77.4	112.4 ± 73.1	51.2 ± 10.3
SMP	682.0 ± 343.0	641.0 ± 293.0	1928.0 ± 621.3	1702.0 ± 774.0

Table 3. Seasonal variations in emission factors (EF). Averages of by the same lower-case letter in rows for a particular location are not significantly different ($p > 0.05$). ESA: Emission source areas; SMS: slurry manure storage; LML: liquid manure lagoon; SMP: solid manure pile.

	EF_{CH4} (kg CH_4 hd^{-1} d^{-1})				EF_{CO2} (kg CO_2 hd^{-1} d^{-1})			
ESA	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Barn	0.002^{a}	0.002^{a}	0.002^{a}	0.001^{b}	0.221^{a}	0.255^{c}	0.211^{a}	0.119^{b}
Paddock	0.004^{a}	0.006^{b}	0.007^{b}	0.004^{a}	0.577^{a}	1.003^{b}	1.250^{c}	0.655^{a}
SMS	0.014^{a}	0.008^{b}	0.014^{a}	0.031^{c}	0.313^{a}	0.438^{b}	0.266^{c}	0.257^{c}
LML	0.024^{a}	0.035^{a}	0.117^{b}	0.088^{c}	0.555^{a}	1.111^{b}	0.743^{c}	0.383^{d}
SMP	0.006^{a}	0.007^{a}	0.030^{b}	0.034^{b}	0.355^{a}	0.403^{a}	0.811^{b}	0.783^{b}

CO_2 flux and seasonal variation

The CO_2 flux in the ESA were analyzed, and the highest daily averages were observed in the SMP during summer (2315 µmol m^{-2} s^{-1}), in the LML and SMS during spring (213 and 238 µmol m^{-2} s^{-1}, respectively), in the paddock during summer (67.3 µmol m^{-2} s^{-1}), and in the barn during spring (54 µmol m^{-2} s^{-1}) (Figure 4). Seasonal averages followed similar trends, with the highest values recorded in the SMP during summer (1928 µmol m^{-2} s^{-1}), in the LML and SMS during spring (173 and 170 µmol m^{-2} s^{-1}, respectively), in the paddock during summer (52.1 µmol m^{-2} s^{-1}), and in the barn during winter (31 µmol m^{-2} s^{-1}). ANOVA and Pearson correlation analyses revealed that CO_2 emissions were not significantly affected by temperature changes and did not show notable seasonal variation ($p > 0.05$). The higher emissions observed in the barn during winter and in the paddock during summer were attributed to animals spending more time in these areas during those seasons (Table 2).

Seasonal variations in total emissions and emission factors

Seasonal variations in total emissions from ESA revealed that the highest CH_4 emission occurred in LML during summer (152 kg CH_4 d^{-1}), while the lowest emissions were measured in the barn during winter (3 kg CH_4 d^{-1}). The CO_2 emissions were highest in the paddock during summer (1625 kg CO_2 d^{-1}) and lowest in the barn during autumn (155 kg CO_2 d^{-1}) (Figure 5).

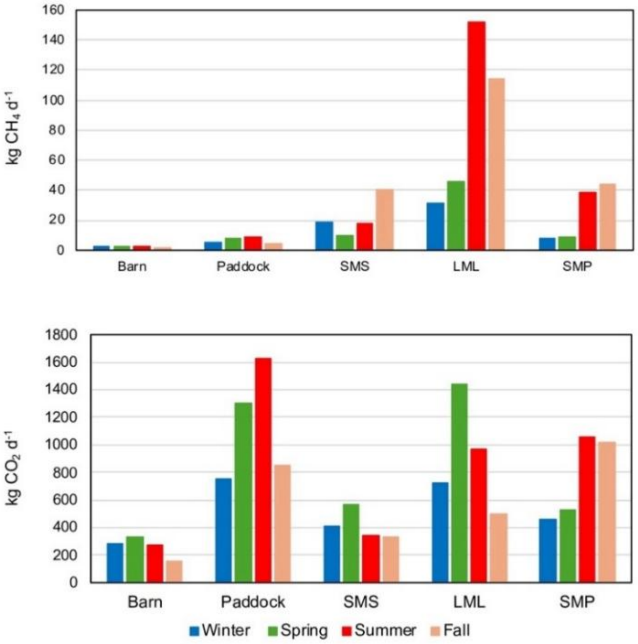

Figure 5. Seasonal variations in total emissions. SMS: Slurry manure storage; LML: liquid manure lagoon; SMP: solid manure pile.

Seasonal emission factors exhibited clear temporal variations for both CH_4 and CO_2 across the ESA (Table 3). The highest CH_4 emission factor (EF_{CH_4}) was recorded in the LML during summer (0.117 kg CH_4 hd^{-1} d^{-1}) ($p < 0.05$). Similarly, the SMP exhibited its maximum $EFCH_4$ during summer (0.03 kg CH_4 hd^{-1} d^{-1}) ($p < 0.05$). In contrast, CH_4 emissions from barn floor and paddock (< 0.01 kg CH_4 hd^{-1} d^{-1}) remained relatively low throughout the year.

For CO_2, the seasonal pattern differed slightly from that of CH_4. The highest CO_2 emission factors ($EFCO_2$) were observed in summer at the paddock (1.250 kg CO_2 hd^{-1} d^{-1}) and in spring at the LML (1.111 kg CO_2 hd^{-1} d^{-1}) ($p < 0.05$). Overall, both CH_4 and CO_2 emissions showed a clear seasonal dependency, with spring and summer contributing the most to the total greenhouse gas (GHG) emissions from the dairy system (Table 3).

Annualized total emissions and emission factors

The contribution of each ESA to the farm's annual total emissions (t CH_4 yr^{-1} and t CO_2 yr^{-1}) is presented in Figure 6. The farm's annual total CH_4 production was estimated at 51.5 t CH_4 yr^{-1}, of which 61.9% (31.3 t CH_4 yr^{-1}) originated from the LML, primarily due to its large manure-covered surface area. These findings indicate that the LML represents the dominant source of CH_4 emissions on the farm. The farm's annual total CO_2 production was estimated at 1272.8 t CO_2 yr^{-1}, of which 33% (414.4 t CO_2 yr^{-1}) originated from the paddock (Figure 6).

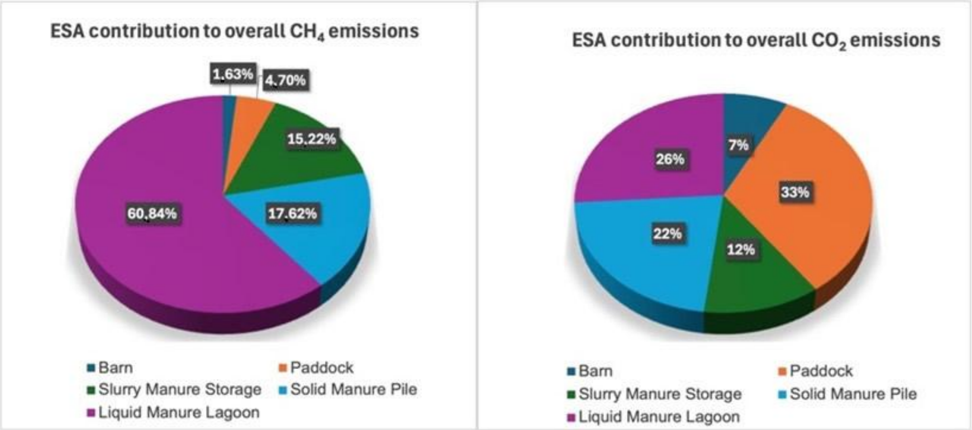

Figure 6. Contribution of each emission source areas (ESA) to the overall annual CH_4 and CO_2 emissions.

Considering the 1300 lactating dairy cows on the farm, the highest annual CH_4 emission factor ($EFCH_4$) among the ESA categories was found in the liquid manure lagoon (LML), with a value of 24.08 kg CH_4 hd^{-1} yr^{-1}, whereas the lowest value was measured at the barn floor (0.65 kg CH_4 hd^{-1} yr^{-1}) ($p < 0.05$). For CO_2, the highest annual emission factor occurred in the paddock (318.79 kg CO_2 hd^{-1} yr^{-1}), while the lowest was again observed at the barn floor (73.61 kg CO_2 hd^{-1} yr^{-1}) ($p < 0.05$). At the whole-farm scale, the annual emission factors for CH_4 and CO_2 were estimated to be 39.59 kg CH_4 hd^{-1} yr^{-1} and 979.11 kg CO_2 hd^{-1} yr^{-1}, respectively (Table 4).

Table 4. Annual emission factors (EF). Averages of by the same lower-case letter in rows for a particular location are not significantly different ($p > 0.05$). ESA: Emission source areas; SMS: slurry manure storage; LML: liquid manure lagoon; SMP: solid manure pile.

	ESA					
Annual EFs	Barn	Paddock	SMS	LML	SMP	Total
kg CH_4 hd^{-1} yr^{-1}	0.65^a	1.86^a	6.02^b	24.08^c	6.97^b	39.59
kg CO_2 hd^{-1} yr^{-1}	73.61^a	318.79^b	116.35^c	255.41^d	214.96^e	979.11

DISCUSSION

In this study, total emissions and emission factors ($EFCH_4$ and $EFCO_2$) for each emission source area (ESA) were calculated based on the instantaneous CH_4 and CO_2 fluxes measured in situ, and clear seasonal differences were identified. The causes of these seasonal variations and the annualized emission estimates are discussed below in relation to previous research.

Seasonal variations in total emissions and emission factors

In this study, $EFCH_4$ values remained consistently higher in LML than in other ESAs throughout the year, reaching a peak of 0.117 kg CH_4 hd^{-1} d^{-1} during summer ($p < 0.05$). These findings are consistent with previous work demonstrating increased CH_4 emissions from manure storage during warm seasons in dairy operations (Cárdenas et al., 2021; Dalby et al., 2021; Fuertes et al., 2023). The seasonal rise in CH_4 emissions is primarily attributed to the large exposed slurry surface area, high organic loading, and enhanced anaerobic decomposition under warm environmental conditions. This pattern confirms that liquid manure storages represent critical CH_4 emission hotspots during warm seasons. Accordingly, slurry management plays a decisive role in total farm-scale CH_4 emissions (Borhan et al., 2011; VanderZaag et al., 2014; Cárdenas et al., 2021; Vechi et al., 2023). Under warm Mediterranean conditions, slurry management strategies become particularly critical for mitigation (Kupper et al., 2020; Dalby et al., 2021). Recent studies indicating that environmental conditions and management interventions significantly influence methanogenic activity and methane emissions in agricultural systems (Wihardjaka et al., 2025; Zavaleta-Cordova et al., 2025). Farm-scale studies indicate that liquid manure is a major emission source in livestock production systems. Furthermore, the pronounced increase in CH_4 formation during extended storage demonstrates that prolonged open-air storage of liquid manure constitutes a significant sustainability concern. These studies also show that effective mitigation is not limited to costly infrastructure, and that low-cost and practical management practices can substantially reduce emissions. Covering the surface of liquid manure with bio-cover materials such as wood and straw mulch (Wei et al., 2021), sawdust (Matulaitis et al., 2015) or biochar (Chen et al., 2021; Verdi et al., 2024; Scotto di Perta et al., 2024) can limit sudden increases in temperature, moderate evaporation processes, and suppress anaerobic decomposition at the surface. The effectiveness and practicality of these bio-covers for reducing emissions have been highlighted in several studies (Matulaitis, 2015; Meiirkhanuly et al., 2020; Ambrose et al., 2023; Verdi et al., 2024).

In contrast, EF_{CH_4} values in barn floors and paddock (< 0.01 kg CH_4 hd^{-1} d^{-1}) areas remained low across all seasons and ESA, with annual $EFCH_4$ values of 0.65 and 1.86 kg CH_4 hd^{-1} yr^{-1}, respectively ($p < 0.05$). This outcome can be explained by the scraper system, which rapidly removes manure from the surface, thereby limiting moisture accumulation and organic loading, maintaining oxygen diffusion, and reducing fermentation potential (El Mashad et al., 2023). Similarly, VanderZaag et al. (2014) reported that shortening manure residence time on barn and paddock surfaces suppresses CH_4 formation, shifting emission contributions primarily to storage facilities.

Another explanation for the low $EFCH_4$ values in our barn and paddock is the use of rubber mats instead of organic bedding material. In other words, the physical and chemical properties of bedding significantly influence barn-level CH_4 emissions.

Field-based comparative data on rubber mat bedding remain limited, whereas studies on organic bedding and compost-bedded pack (CBP) systems consistently report higher CH_4 emissions. For example, Fuertes et al. (2023) observed that $EFCH_4$ in CBP systems in Lleida, Spain, increased from 0.011 to 0.059 kg CH_4 hd^{-1} d^{-1} from winter (5.3 °C) to summer (34.9 °C), representing a 5.2-fold rise, and that daily tilling led to transient CH_4 flux spikes up to 60-fold. VanderZaag et al. (2014) reported high $EFCH_4$ (0.730 kg CH_4 hd^{-1} d^{-1}) from barn floors using sand bedding in Canada. Similarly, Won et al. (2020) estimated an annual $EFCH_4$ of 3.12 kg CH_4 hd^{-1} yr^{-1} from sawdust-manure bedding mixtures in Korea.

These reported $EFCH_4$ values are substantially higher than those observed in our barn without organic bedding. Organic bedding materials (e.g., sawdust, straw, compost) contain high organic matter and moisture, promoting microbial activity and urease-driven degradation, thereby enhancing CH_4 formation (Le Riche et al., 2017; Fuertes et al., 2023). In contrast, rubber mats, as used in this study, are inert and non-absorbent, allowing urine-feces mixtures to be promptly removed, limiting moisture retention, organic loading, and anaerobic micro-niche development. This suppresses methanogenic activity and consequently reduces barn CH_4 emissions (Le Riche et al., 2017). Although field-based evidence on the emission impacts of rubber mat flooring systems remains limited, the results of this study indicate that barns equipped with rubber mats and scraper systems may exhibit comparatively lower in-barn CH_4 emissions. These findings provide empirical evidence for a relatively under-documented aspect of barn management and highlight the importance of further research on bedding materials and barn-floor design in relation to greenhouse gas mitigation.

Regarding CO_2, seasonal patterns differed from CH_4. The highest $EFCO_2$ values were observed in the paddock (1.250 kg CO_2 hd^{-1} d^{-1}) and LML (1.111 kg CO_2 hd^{-1} d^{-1}) during spring and summer ($p < 0.05$). This is linked to the combined influence of temperature and moisture on microbial respiration and organic C oxidation (Won et al., 2020). Conversely, CO_2 emissions inside the barn remained relatively low due to the scraper system limiting organic matter accumulation (El Mashad et al., 2023).

Annualized total emissions and emission factors

In this 1300-cow dairy, total CH_4 emissions were 51.5 t CH_4 yr^{-1}, corresponding to an $EFCH_4$ of 39.59 kg CH_4 hd^{-1} yr^{-1}. The LML contributed the majority of these emissions (31.3 t CH_4 yr^{-1}, $EFCH_4$ = 24.08 kg CH_4 hd^{-1} yr^{-1}; 61.9%

of total) ($p < 0.05$). Total CO_2 emissions were 1273.0 t CO_2 yr^{-1} (EF_{CO2} = 979.11 kg CO_2 hd^{-1} yr^{-1}), with paddocks accounting for 414.4 t CO_2 yr^{-1} (318.79 kg CO_2 hd^{-1} yr^{-1}), representing 33% of total ($p < 0.05$) (Table 4).

Similarly, Borhan et al. (2011) reported that 89% of total CH_4 emissions (29.44 t CH_4 yr^{-1}; 58.87 kg CH_4 hd^{-1} yr^{-1}) in a 500-cow dairy with a flushing system originated from liquid manure storage. The higher emissions observed in that study are attributed to the substantially larger liquid manure volume generated by the flushing process. In contrast, the scraper system in our study limited liquid volume entering LML, thereby reducing anaerobic decomposition potential and CH_4 formation (El Mashad et al., 2023).

CONCLUSIONS

This study quantified CH_4 and CO_2 fluxes from major emission source areas (ESAs) of a high-capacity commercial dairy farm under warm Mediterranean conditions using in situ measurements. The results showed clear seasonal variability, with substantially higher emissions during warm periods. At the whole-farm scale, the liquid manure lagoon was identified as the dominant source of CH_4 emissions, followed by the solid manure pile, whereas emissions from barn floors were comparatively lower. Emission factors calculated for each ESA confirmed that manure storage systems play a decisive role in determining total farm-scale greenhouse gas emissions. The marked increase in emissions from liquid manure storage during warm periods highlights the importance of storage conditions in warm climates. Overall, the findings indicate that management of liquid manure systems is a key component of mitigation strategies for dairy farms operating under Mediterranean environmental conditions. The field-based measurements presented in this study provide representative data for improving emission inventories and supporting the development of more effective manure management practices under warm climate conditions.

Author contribution

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