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Enteric Methane Production, Yield, and Intensity in Smallholder Dairy Farming Systems in Peri-Urban Areas of Coastal West African Countries: Case Study of Benin

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ABSTRACT

Enteric methane (eCH4) is a major environmental pollutant emitted by ruminants. To target mitigation measures, it is necessary to accurately estimate GHG emissions from livestock farming. Until now, milk-producing farms in the peri-urban areas of South Benin are pasture-based systems, and have been largely neglected by international research. Therefore, this study estimates eCH4 emissions from pasture-based peri-urban dairy farms across four different animal categories during dry and wet seasons. Six herds were selected for field measurements; one representative animal was selected per category from each herd and its body weight estimated. Subsequently, the selected animals were closely monitored on pasture for three consecutive days. Direct observation of their behavior and the hand-plucking method were used to mimic the animals' selective foraging and to sample parts of the different plant species consumed in proportion to their, to determine the quality of their daily diet. The nutrient content and digestibility of the collected feed samples were assessed using near-infrared spectroscopy. Additionally, 30 herds were monitored bi-monthly during a 12-month period to collect all input and output data, including milk yields. Annual enteric methane (eCH4) emissions per animal category were estimated using the IPCC Tier 2 method. Subsequently, the eCH4 intensities of lactating cows were calculated per kg of fat-protein corrected milk (FPCM). All statistical analyses were performed using R software. Overall, the average annual eCH4 production was 40.6 kg/head/year and the eCH4 yield was 20.3 g/kg of dry matter intake, with significant differences between seasons and no differences between animal categories. Regardless of season, older animals yielded higher eCH4 outputs. The average eCH4 production per kg of live weight was 0.48 g for both seasons. The overall eCH4 intensity (g CH4/kg FPCM) recorded during the wet season (74.3) was higher than that recorded during the dry season (70.5).

1 | Introduction

In most sub-Saharan African countries, the demand for animal-source food in urban areas has been increasing steadily with population growth and urbanization (Abu Hatab, Cavinato, and Lagerkvist 2019). Indeed, rapid urbanization has fostered a nutritional shift characterized by a growing demand for foods of animal origin, such as milk and milk products (van Berkum et al. 2017). Although milk is highly perishable, there is poor infrastructure for its transportation from rural areas to meet the increasing demand in urban and peri-urban areas (Herrero et al. 2014). Hence, milk-producing farms have moved from rural areas to the edges of cities to benefit from well-developed and reliable infrastructure, such as roads and electricity supply (Chamberlin and Jayne 2013), making fresh milk available at affordable prices to urban dwellers (D'Haene and D'Haese 2019). However, despite its importance, the development of smallholder peri-urban dairy production has received inadequate public and institutional support in most sub-Saharan African countries (Duguma 2022). In Benin, its presence has even been overlooked in the National Strategic Plan for the Development of Urban and Peri-Urban Agriculture adopted in 2015 (FAO-MAEP 2015).

Various peri-urban dairy farming systems exist in West Africa (Dossa et al. 2015; Roessler, Mpouam, and Schlecht 2019), and despite the emergence of zero-grazing practices based on cut-and-carry fodder and the use of commercial feedstuffs (Roessler, Mpouam, and Schlecht 2019), year-round grazing of cattle on communal grazing lands remains the dominant feeding strategy. In the peri-urban areas of Bobo-Dioulasso in Burkina Faso, animals graze at several locations, with an average daily grazing time of 9–12 h (Dossa et al. 2015). A similar observation was made by Yassegoungbe et al. (2022) in the peri-urban area of South Benin, where milk-producing farmers rely solely on communal grazing lands to feed their animals.

While pasture-based dairy farming requires a large area of land for fodder production, peri-urban dairy production is increasingly affected by rapid urbanization, which generally results in competition for land and shrinkage of grazing land in particular (Duguma 2022). The latter is associated with a shortage of green fodder, whose nutritive quality varies significantly between dry and wet seasons (Amole et al. 2022). Low feed intake and poor forage quality are known to negatively affect milk yield and the animals' nutritional status, leading to high emissions of nitrogen and greenhouse gases, particularly enteric methane (eCH4), per kilogram of milk produced (Dini et al. 2018). Recent studies in Ethiopia (Balcha et al. 2022; Feyissa et al. 2023) have revealed that peri-urban dairy farming has a significantly lower enteric methane emission intensity than rural-based production (Balcha et al. 2022). Since enteric methane emissions are very dependent on farm management (Rotz, Montes, and Chianese 2010), differences can be expected between different peri-urban farm types that have been recently described for coastal Benin (Yassegoungbe et al. 2022). To date, however, no studies have been published on GHG emissions from smallholder peri-urban dairy cattle farming systems in West Africa.

Similar to national inventories in sub-Saharan Africa, previous attempts to provide eCH4 estimates for livestock production systems in Benin (Kouazounde et al. 2015; Agossou and Koluman 2022) were based on default emission factors published by the Intergovernmental Panel on Climate Change (IPCC) using the animals' energy requirements rather than the actual amount of energy consumed. Furthermore, they did not consider the specific context of peri-urban production systems. Therefore, the objective of this study was to estimate enteric methane emissions from peri-urban dairy cattle farming systems in southern Benin using the IPCC Tier 2 method and gross energy intake derived from field data.

2 | Materials and Methods

2.1 | Study Area

The study was conducted in the peri-urban area of South Benin, specifically in three municipalities in the coastal zone (Figure 1) around Cotonou, the country's largest city. Yassegoungbe et al. (2022) provided a detailed description of this research location.

The natural pastures in the study area are characterized by several herbaceous species dominated by species from the Poaceae, Fabaceae, Asteraceae, and Cyperaceae families. Indeed, the ecological and climatic conditions of this area are favorable to the growth of Poaceae species that constitute the essential diet of ruminants but are of poor nutritional quality (Koura et al. 2022). In contrast, hydromorphic areas and floodplains are unfavorable to the growth of palatable C4 grasses, such as *Panicum maximum* and *Andropogon gayanus*, which are rarely found on coastal pastures, but host swamp species such as *Paspalum vaginatum* and *Cyperus articulatus*, often very productive but of low nutritional value (Koura et al. 2022).

2.2 | Data Collection

2.2.1 | Farms and Animals

A total of 30 farms distributed equally across six pasture-based dairy farm types were included in this study. These farm types had previously been defined (Yassegoungbe et al. 2022) in the same study area. The herd characteristics of the farms are presented in Table 1. Irrespective of farm type, the animals' diet was exclusively based on naturally growing pasture vegetation. As part of the study, one representative herd with at least 10 animals was selected from each farm type. Then, four animals, representing each a specific category (one bull, one lactating cow, one steer, and one heifer), were chosen to be monitored on pasture once per season. Before their monitoring, the animals' thoracic perimeter was measured with a tape to determine their live weight (LW) using regression equations developed for each breed and animal category as follows:

For zebu cattle (Touré et al. 2018):

- Steer and heifer 1-3 years:

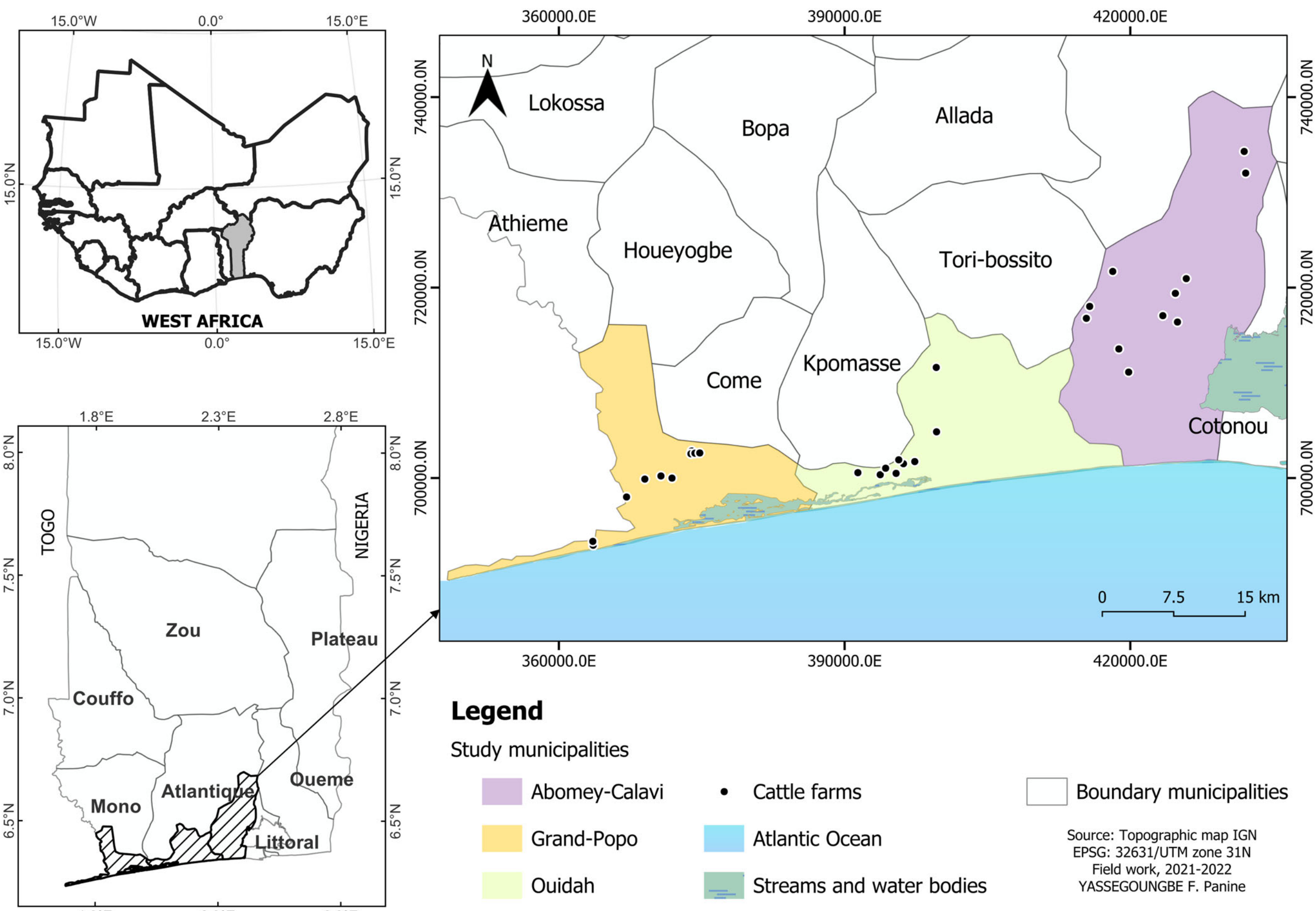

FIGURE 1 | Map of South Benin showing the study area and surveyed municipalities.

TABLE 1 | Characteristics of cow milk production systems in the peri-urban area of South Benin; data depict either frequency (%) or means ± standard error (SE).

Variables	Mean ± SE
Total herd size (*n*)	54.9 ± 2.88
Herd structure (%)	
Bulls	4.9 ± 0.28
Cows	42.6 ± 0.91
Steers	10.2 ± 0.52
Heifers	18.4 ± 0.83
Calves	23.9 ± 0.52
Dominant breeds in herd (%)	
Local taurine	64.8
Zebu White Fulani	31.6
Zebu Goudali	3.6

Source: Yassegoungbe et al. (2022).

$$Y = 0.01899X^2 - 1.912098X + 101.335727. \quad (1)$$

- Cow > 3 years:

$$Y = 0.038932X^2 - 8.243556X - 640.534367. \quad (2)$$

- Bull:

$$Y = 0.036282X^2 - 5.740076X + 309.491414. \quad (3)$$

For taurine cattle (Vanvanhossou, Diogo, and Dossa 2018):

All categories:

$$Y = (1.33 \times 10) - 4X^{2.89}, \quad (4)$$

where Y is the predicted live weight (kg), and X is the thoracic perimeter (cm).

2.2.2 | Animal Monitoring, Estimation of Feed Intake at Pasture and Diet Quality Assessment

The four animals selected from each herd were monitored on pasture once in the wet season (September–October 2021) and once in the dry season (December–January 2022). Each animal was monitored and closely observed by the same person throughout the day over a 3-day monitoring period. Six observation times (3 in the morning and 3 in the afternoon) were defined for every day, each lasting 5 min, during which direct observation of the animal's feeding behavior and the hand-plucking method (Meuret et al. 1985; Guérin et al. 1986) were used to mimic the animal's foraging behavior and to sample, in a manner proportional to the animal's choice, parts of the different plant species consumed by the monitored animal. Daily plucked samples were collected into large paper bags to represent the quality of the daily consumed diet; they were air-dried in the shade of a roof for 5 days, milled to 2 mm particle size (Retsch-SK100, Hann, Germany), and dried in a forced-air circulation oven (Memmert Models 30-1060, Baar, Germany) at 65°C for 72 h to determine the dry matter (DM) content. The dried samples of daily diets were pooled into one sample per category of monitored animals per day, ground at 2 mm using a Retsch mill, and stored in tightly closed bags until transportation to the laboratory for chemical analysis.

A daily subsample of 250-g DM of each pooled diet sample per animal category was analyzed at the laboratory of CIRDES (Centre International de Recherche-Développement sur l'Elevage en zone Subhumide) in Bobo Dioulasso, Burkina Faso, using near-infrared spectroscopy (NIRS). NIRS spectra were collected for each sample using a spectrometer (Tango model, Bruker Optik, Ettlingen, Germany) to predict, with established regression equations (Guérin et al. 1986), its contents of crude ash, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), in vitro dry matter digestibility (IVDMD), and in vitro organic matter digestibility (IVOMD).

2.2.3 | Calculation of Dry Matter and Energy Intake on Pasture

The animals' dry matter intake on pasture was determined according to established equations (Intergovernmental Panel on Climate Change 2006) as a function of live weight, metabolic weight, and digestible energy as follows:

Growing and finishing cattle (steer and heifer)

$$\mathrm{DMI} = \mathrm{LW}^{0.75} \times \left[\frac{(0.2444 \times \mathrm{NEma}) - (0.0111 \times \mathrm{NEma}^2) - 0.472}{\mathrm{NEma}}\right]. \quad (5)$$

Mature beef cattle (bull)

$$\mathrm{DMI} = \mathrm{LW}^{0.75} \times \left[\frac{(0.0119 \times \mathrm{NEma}^2) + 0.1938}{\mathrm{NEma}}\right]. \quad (6)$$

Mature dairy cows (cow)

$$\mathrm{DMI} = \left(\frac{5.4 \times \mathrm{LW}}{500}\right) / \left(\frac{100 - \mathrm{DE\%}}{100}\right), \quad (7)$$

where

DMI is the daily amount of dry matter (DM) ingested by the animal (expressed in kg DM); LW is the live weight expressed in kg; $LW^{0.75}$ is the metabolic weight (MW) expressed in kg; NEma is the dietary net energy concentration of the diet: we used the average (4.5) of the IPCC default values for low-energy concentration diets ranging from 3.5 to 5.5; and DE% is the digestible energy expressed as a percentage of gross energy: we used the average (50%) of the IPCC default values for low-energy concentration diets ranging from 45% to 55%.

The daily gross energy intake (GEI) per animal was calculated using the formula proposed by Pinares-Patiño et al. (2003), as follows:

$$\mathrm{GEI(MJ/head/day)} = \mathrm{GE} \times \mathrm{DMI}, \quad (8)$$

where

GE is the gross energy contained in the daily feed ration (in MJ/kg DM), and DMI is the daily amount of DM ingested by the animal, as determined above (Equations 5–7).

GE was calculated from the crude protein content (CP) of the daily consumed diet as obtained from feed analyses and the regression equation proposed by Richard et al. (1990) for natural grasses and legumes of tropical pastures.

$$\mathrm{GE(kcal/kg\ OM)} = 4516 + 1.646\mathrm{CP}, \quad (9)$$

where

CP is the crude protein contained in the ration (g/kg OM).

2.2.4 | Determination of Milk Yield, Milk Composition, and Fat-Protein Corrected Milk

Milk offtake was measured in each monitored lactating cow in the morning before grazing every 2 weeks according to the methodology proposed by Hiernaux et al. (2017). In the present study, at each hand milking session, the milk from each cow was poured into a transparent plastic pot and weighed using an ordinary digital kitchen weigh scale to determine individual production before pooling the herd's production. The total amount of milk produced per cow per day (i.e., milk yield) was calculated by adding the measured milk offtake to the estimated proportion of milk sucked by the calf according to Sossouve et al. (2023). In the latter study, the calf was weighed before and after suckling, and the difference in weight was taken as the amount of milk consumed. Since this study was carried out in the same area and involved the different breeds of cattle used in the farming systems of our study, the estimated milk consumption of the calves was added to the measured production of its dam. Calves were weighted using a cage platform connected to an electronic balance (XR-3000 Tru-Test Ltd., Auckland, New Zealand). After milking, a milk sample of 50 mL was taken, and its actual protein and fat contents were determined using a portable milk analyzer (Milkotester Master Classic LM2-P1, Bulgaria). Fat-protein-corrected milk (FPCM) was calculated using the formula proposed by Food and Agriculture Organization of the United Nations (2010) as follows:

$$\mathrm{FPCM(kg)} = \mathrm{milk\ yield(kg)} \times [0.337 + (0.116 \times \mathrm{Fat(\%)}) + (0.06 \times \mathrm{Protein(\%)})]. \quad (10)$$

2.2.5 | Estimation of Enteric Methane Production, Yield, and Emission Intensity

Enteric methane production (g/day) and yield (g/kg DMI) were calculated for each animal category (cow, heifer, bull, and steer) in the herd using IPCC Tier 2 equations (Intergovernmental Panel on Climate Change 2006). The daily eCH4 production per animal head was estimated as follows:

$$\text{eCH4(g/day)} = (\text{GEI} \times \text{Ym})/0.05565, \tag{11}$$

where

GEI is the daily Gross Energy Intake; Ym is the methane conversion factor (the default value of 6.5% for cattle fed on pasture was used), which corresponds to the percentage of gross energy in the diet converted to methane; and the factor of 55.65 (MJ/kg CH4) represents the energy value of methane.

The animals' gross energy intake was calculated using Equation (8) instead of estimates based on the net energy requirements for maintenance, activity, work, lactation, pregnancy, and growth of young animals (Intergovernmental Panel on Climate Change 2006).

The emission intensity (EI) of lactating cows was determined as follows:

$$\text{EI} = \text{eCH4(cow)/FPCM}, \tag{12}$$

where

eCH4 (cow) is the enteric methane emission in g CH4/cow/day; FPCM is the fat- and protein-corrected milk yield in kg/cow/day; and EI is the eCH4 emission intensity in g/kg FPCM.

2.2.6 | Statistical Analysis

Data entry and parameter calculations were performed using Excel 2013 spreadsheets. For each monitored herd, live weight, dry matter intake, gross energy intake, and eCH4 production, yield, and intensity were calculated per animal category and the respective number of animals in the herd. Using R software, descriptive statistics (mean and standard error) were calculated for each variable and animal category. The FactoMineR and Factoextra packages were used for data visualization and analysis. Means were compared between animal categories using the non-parametric Kruskal–Wallis test and the post-hoc Wilcoxon pairwise test in R. Differences were considered significant at $p \leq 0.05$ for all tests.

3 | Results

3.1 | Feed Quality and Intake of Dry Matter and Gross Energy

The chemical composition and nutritive value (crude ash, DM, CP, NDF, ADF, ADL, and IVOMD) of the selected diet did not vary significantly ($p > 0.05$) between animal categories, but showed significant differences ($p < 0.05$) between seasons (Table 2). The average ash content of the diet was higher in the dry season (12.4% ± 0.31) than in the wet season (11.6% ± 0.33). In contrast, the average CP content was higher in the wet season (11.6% ± 0.23) than in the dry season (9.6% ± 0.21). The concentrations of NDF and ADF were considerably higher in the wet season (62.4% ± 0.61% and 40.0% ±0.30) than in the dry season (55.3% ± 0.52% and 36.2% ± 0.33), whereas the average ADL content was significantly lower in the wet season (6.2% ± 0.12) than in the dry season (8.9% ± 0.27). The in vitro digestibility of organic matter (IVOMD) was higher (48.6% ± 0.23) in the wet season (Table 2).

The estimated DMI (kg/animal/day) ranged from 3.6 to 7.8 and varied significantly ($p < 0.05$) between animal categories and seasons (Table 3). The lowest average DMI values were obtained for steers in the dry (3.6 kg) and wet (4.3 kg) seasons, whereas the highest average values were observed for bulls in the dry (7.3 kg) and wet (7.8 kg) seasons.

The calculated GEI (MJ/head/day) also varied significantly ($p < 0.05$) between animal categories and seasons. Across animal categories and seasons, the GEI values ranged from 62.2 to 137.4, with an average value of 90.0 in the dry season and 100.5 in the wet season. The bull category, followed by lactating cows, had the highest gross energy intake in both seasons (Table 3).

3.2 | Milk Yield and Composition

Milk yield (kg/day) varied significantly ($p < 0.05$) between seasons (Table 4), with higher yields in the dry season (1.7 ± 0.04) than in the wet season (1.6 ± 0.05). Likewise, the average milk protein and fat content varied significantly between seasons ($p < 0.05$), whereby milk fat content was higher in the wet (4.4% ± 0.10) than in the dry season (3.7% ± 0.08), and milk protein content was higher in the dry (3.8% ± 0.03) than in the wet season (3.6% ± 0.01). Consequently, the yield of FPCM (kg/cow/day) was the same in both seasons (Table 4).

3.3 | Enteric Methane Production, Yield, and Emission Intensity

Table 5 presents the results of eCH4 production (g/animal/day) and eCH4 yield (g/kg DMI). Irrespective of animal category and season, the animals produced an average of 111.2 g eCH4/day/head, with significant differences ($p = 0.031$) between dry (105.1 g) and wet (117.3 g) seasons. Older animals (bulls and cows) emitted higher amounts ($p \leq 0.001$) of eCH4 per day regardless of season, with bulls having the highest eCH4 production in both wet and dry seasons, whereas steers produced the lowest daily amount of eCH4 across seasons.

The average eCH4 yields (g/kg DMI) ranged from 20.0 to 20.6 irrespective of animal category and season, although the seasonal differences (20.5 in the wet season, 20.1 in the dry season) were significant ($p \leq 0.001$). Expressed in g/kg of live weight, eCH4 yields ranged from 0.44 to 0.53, with an average of 0.48 irrespective of season ($p > 0.05$).

TABLE 2 | Seasonal variation in the chemical composition (% DM) of the daily grazed diet of cattle in the peri-urban area of South Benin as determined by NIRS; data depict means ± standard error.

Seasons	Parameter							
	DM* ($n = 72$)	Crude ash ($n = 72$)	CP ($n = 72$)	NDF ($n = 72$)	ADF ($n = 72$)	ADL ($n = 72$)	IVOMD ($n = 72$)	GE (MJ/kg DM) ($n = 72$)
Dry season	$36.3^a \pm 1.05$	$12.4^a \pm 0.31$	$9.6^b \pm 0.21$	$55.3^b \pm 0.52$	$36.2^b \pm 0.33$	$8.9^a \pm 0.27$	$44.7^b \pm 0.68$	$17.2^b \pm 0.07$
Wet season	$26.6^b \pm 0.85$	$11.6^b \pm 0.33$	$11.6^a \pm 0.23$	$62.4^a \pm 0.61$	$40.0^a \pm 0.30$	$6.2^b \pm 0.12$	$48.6^a \pm 0.23$	$17.5^a \pm 0.06$
P ≤	0.001	0.033	0.001	0.001	0.001	0.001	0.001	0.001

Note: Within columns, values with different superscript letters are significantly different at $p \leq 0.05$.
Abbreviations: ADF, acid detergent fibers; ADL, acid detergent lignin; CP, crude protein; *n*, number of records per season, NDF, neutral detergent fibers; IVOMD, In vivo digestibility of organic matter.
*DM in % of fresh matter.

The estimated annual enteric methane production from an individual animal (eCH4 (i)) ranged from 29.2 to 56.3 kg/head/year, with significant differences between animal categories (Table 5): Bulls were the highest eCH4 emitters, whereas the lowest eCH4 production was recorded in steers.

Calculated eCH4 emissions intensities (g/kg FPCM) of lactating cows were slightly higher in the wet season (74.3) than in the dry season (70.5), but the difference was not significant (Table 4).

4 | Discussion

4.1 | Diet Quality and Feed Intake

In the peri-urban dairy farms under study in southern Benin, cattle are fed exclusively on natural pastures without receiving any additional feed (Yassegoungbe et al. 2022). Under such conditions, their enteric methane emissions are directly related to DMI and the nutritional quality of the feed consumed on pasture (Dini et al. 2018; Nunes et al. 2023). The calculated DMI values (kg/head/day) ranged from 3.6 to 7.8. Expressed in g/kg LW/day, they amounted to 23.0 and 22.5 for bulls, 21.6 for cows, 26.6 and 25.5 for steers, and 25.1 and 23.8 for heifers, respectively, in the dry and wet seasons, with an overall average value of 23.7 g/kg LW/day. The latter value was higher than the intake of cattle reported by Assouma et al. (2018) for rural areas of northern Senegal (17.2 g DM/kg LW) but similar to the findings of Amole et al. (2022) in the Sahelian zone of Mali and Senegal (18–27 g DM/kg LW). Because we estimated feed and gross energy intake based on the animals' live weight, the quality of the grazed diet, and established equations, differences in methodological approaches might, to a certain extent, explain the differing results. Other influential factors are differences in the botanical composition and phenological stage of the grazed pastures, daily pasturing time, and supplementation practices (Dini et al. 2018). Previous GHG inventories for the livestock sector in Benin (Kouazounde et al. 2015; Agossou and Koluman 2022) and other sub-Saharan African countries were based exclusively on secondary data to estimate animal feed requirements and intake. The high DMI values obtained in the present study seem plausible because the availability of pasture biomass in the peri-urban area of southern Benin is good, due to high rainfall, despite the fact that land is continuously being diverted for cropping, residential buildings, and other uses (Yabi and Afouda 2012). In the current study, a higher DMI was associated with a higher ADL and a lower CP content of the (hand-plucked) diet samples. The average ADL content of the plant parts selected by grazing cattle was higher in the dry season than in the wet season. However, despite the NDF and ADF content of the diet samples being higher in the wet season than in the dry season, the reduced lignification and the higher CP content resulted in a higher IVOMD in the wet season. These results confirm the low quality of natural pasture vegetation in the dry season due to the higher fiber content (Müller et al. 2019). Interestingly, the nutrient content of the animals' diet did not vary significantly between animal categories in the same herd, which can be explained by the limited choice of different types of forage in the grazed areas, as explained in Section 2.1.

TABLE 3 | Seasonal variation in daily feed dry matter intake (DMI) and gross energy intake (GEI) of cattle in the peri-urban dairy farming of South Benin, data depict means ± standard error.

		Animal category				
Variables	**Overall**	**Bull**	**Cow**	**Steer**	**Heifer**	$p \leq$
LW (kg)						
Dry season	224 ± 10.86	321^{a} ± 17.62	267^{b} ± 12.58	143^{c} ± 14.76	165^{c} ± 4.64	0.001
Wet season	253 ± 10.89	351^{a} ± 18.00	282^{b} ± 8.81	177^{c} ± 20.30	203^{c} ± 7.56	0.001
$p \leq$	0.048	0.584	0.406	0.323	0.001	
DMI (kg/head)						
Dry season	5.2 ± 0.21	7.3^{a} ± 0.31	5.8^{b} ± 0.27	3.6^{c} ± 0.28	4.1^{c} ± 0.09	0.001
Wet season	5.7 ± 0.21	7.8^{a} ± 0.30	6.1^{b} ± 0.19	4.3^{c} ± 0.37	4.8^{c} ± 0.14	0.001
$p \leq$	0.048	0.584	0.406	0.323	0.001	
DMI (g/kg LW)						
Dry season	24.1 ± 0.30	23.0^{c} ± 0.37	21.6^{c} ± 0.00	26.6^{a} ± 0.68	25.1^{b} ± 0.18	0.001
Wet season	23.4 ± 0.28	22.5^{bc} ± 0.28	21.6^{c} ± 0.00	25.5^{a} ± 0.79	23.8^{b} ± 0.23	0.001
$p \leq$	0.042	0.584	1.000	0.323	0.001	
GEI (MJ/head)						
Dry season	90.0 ± 3.77	126.9^{a} ± 5.62	100.1^{b} ± 4.84	62.2^{c} ± 4.94	70.6^{c} ± 1.93	0.001
Wet season	100.5 ± 3.66	137.4^{a} ± 5.22	105.1^{b} ± 3.33	74.6^{c} ± 6.54	84.7^{c} ± 2.64	0.001
$p \leq$	0.031	0.584	0.443	0.152	0.001	

Note: Within rows, values with different superscript letters are significantly different at $p \leq 0.001$.
Abbreviation: LW, Live weight.

TABLE 4 | Seasonal variation in daily milk yield, milk composition, and eCH4 emission intensity (EI) of lactating cows in peri-urban dairy farming in South Benin, data depict means ± standard error.

	Variables					
Seasons	**Milk offtake (kg/cow)**	**Milk yield (kg/cow)**	**Milk fat content (%)**	**Milk protein content (%)**	**FPCM (kg/ cow/day)**	**EI (g CH4/ kg FPCM)**
Dry season	1.2^{a} ± 0.03	1.7^{a} ± 0.04	3.7^{b} ± 0.08	3.8^{a} ± 0.03	1.7 ± 0.04	70.5 ± 2.59
Wet season	1.1^{b} ± 0.04	1.6^{b} ± 0.05	4.4^{a} ± 0.10	3.6^{b} ± 0.01	1.7 ± 0.05	74.3 ± 2.98
$p \leq$	0.009	0.012	0.001	0.001	0.173	0.548

Note: Within columns, values with different superscript letters are significantly different at $p \leq 0.001$.
Abbreviations: EI, emission intensity; FPCM, fat-protein-corrected milk.

4.2 | Gross Energy Intake and Enteric Methane Emissions

In the current study, the calculation of gross energy intake (GEI; MJ/head/day) accounted for the CP content of the diet. GEI values ranged from 62.2 to 137.4 across animal categories and seasons, with an overall mean of 95.2, which agrees with average values of 72.1 and 100.9 calculated by Kouazounde et al. (2015) for taurine and zebu breeds, respectively, based on their energy requirements. Therefore, our results do not raise concerns about the appropriateness of the method for estimating GEI for the main categories of ruminants kept under tropical conditions; the values can also be used for national greenhouse gas inventories. The comparatively lower GEI obtained in the current study directly affected the calculated eCH4 values because GEI is a key variable for its estimation (Equation 11), together with the methane conversion factor Ym. The value of the latter also varies according to animal category, production level, and region (Islam et al. 2022). Therefore, to reduce possible errors in estimating eCH4 emissions, it is necessary to estimate Ym for each country or region (Nunes et al. 2023). However, the values of Ym for animals raised exclusively on seasonally varying natural pasture vegetation are poorly documented (Islam et al. 2022). The Ym default value (6.5% ± 1.0%), previously developed for low-yielding dairy cows and grazing cattle of any category, as proposed by Intergovernmental Panel on Climate Change (2006) in the Tier 2 methodology, was used in this study.

The mean value of 40.6 obtained for eCH4 production (kg CH4/head/year) in this study is significantly lower than the value of 57.9 reported by Agossou and Koluman (2022), but similar to the production of 39.5 reported by Kouazounde et al. (2015). First, it should be noted that most of the data used in these two case studies from Benin came from information available in the literature, in contrast to our study, where some data were collected in the field, and others came from literature estimates. Second, some of the primary data used in the

TABLE 5 | Seasonal variation in enteric methane (eCH4) production and yield from cattle raised on pasture in the peri-urban area of South Benin, data depict means ± standard error.

Variables	Overall	Animal category				$p \leq$
		Bull	Cow	Steer	Heifer	
eCH4 production (g/day/head)						
Dry season	105.1 ± 4.40	148.2[a] ± 6.56	116.9[b] ± 5.65	72.6[c] ± 5.77	82.4[c] ± 2.25	0.001
Wet season	117.3 ± 4.25	160.5[a] ± 6.10	122.7[b] ± 3.89	87.2[c] ± 7.64	99.0[c] ± 3.08	0.001
$p \leq$	0.031	0.584	0.443	0.152	0.001	
eCH4 yield (g/kg DMI)						
Dry season	20.1 ± 0.08	20.3 ± 0.15	20.2 ± 0.09	20.0 ± 0.15	20.0 ± 0.20	0.247
Wet season	20.5 ± 0.07	20.6 ± 0.12	20.1 ± 0.20	20.5 ± 0.10	20.6 ± 0.13	0.338
$p \leq$	0.001	0.308	0.767	0.002	0.012	
eCH4 (g/kg LW)						
Dry season	0.48 ± 0.06	0.47[b] ± 0.01	0.44[b] ± 0.06	0.53[a] ± 0.01	0.50[a] ± 0.00	0.001
Wet season	0.48 ± 0.01	0.46[bc] ± 0.01	0.44[c] ± 0.00	0.52[a] ± 0.02	0.49[ab] ± 0.00	0.001
$p \leq$	0.348	0.673	0.767	0.815	0.134	
Annual eCH4 production (kg/head/year)						
—	40.6 ± 1.52	56.3[a] ± 1.95	43.7[b] ± 1.52	29.2[c] ± 2.35	33.1[c] ± 0.87	0.001

Note: Within rows, values with different superscript letters are significantly different at $p \leq 0.001$.
Abbreviations: DMI, dry matter intake; LW, Live weight.

previous studies were specific to the Sudanian agro-ecological zone, whose climate and vegetation differ from those of the coastal area. Finally, these studies did not account for seasonal variations in the availability and quality of pasture vegetation.

The eCH4 production values obtained in this study were within the range of reference values (31–49) proposed by Intergovernmental Panel on Climate Change (2019) for African countries, without using their individual national data. This result does not support the claim by Mottet and Assouma (2024) that using the IPCC approach leads to a 36%–76% overestimation of actual eCH4 emissions in the pastoral and agro-pastoral production systems in sub-Saharan Africa. These authors argue that in the Tier 2 approach, DMI and GEI are calculated according to the energy requirements of the animals and are overestimated by 26%–71%. This confirms the need for quantitative field data that considers the diversity of production environments in each country when determining emission factors for strategic and operational decisions to limit the contribution of livestock to climate change (Katayanagi et al. 2016). To this end, determining the quantitative and qualitative feed intake of animals raised on natural pastures in extensive production systems is critical. As highlighted by Maccarana et al. (2016), the nutrient concentration of animal feed dry matter (NDF, CP, and crude lipids) affects eCH4 production.

Our calculations showed that older animals, namely bulls, followed by lactating cows, were the highest eCH4 emitters. This finding is consistent with the results of previous studies (Agossou and Koluman 2022; Nunes et al. 2023). However, as suggested by Dini et al. (2018), eCH4 emissions from cattle production systems based on low-quality natural vegetation should be expressed per kg live weight and not per animal, because animals are not always comparable in terms of live weight and breed.

Regardless of the animal category, the average eCH4 yield per kg LW (dry and wet season: 0.48) and per kg DMI (dry season: 20.1, wet season: 20.5) were lower than those reported by Slayi et al. (2023) for Nguni and Bonsmara cows from South Africa kept exclusively on communal pastures (0.69 g CH4/kg LW and 26.4 g CH4/kg DMI). Higher values (26.5–32.8 g/kg DMI) were also obtained for beef cows in South Africa (Mapfumo et al. 2018). These differences in eCH4 yield can be explained by differences in DMI, with the animals in our study consuming less forage (3.6–7.8 kg DM/day) than the Bonsmara and Nguni (9.93 kg DM/day) in South Africa (Slayi et al. 2023), as there is a high positive correlation between eCH4 production and DMI in animals fed only forage (Dini et al. 2018). Yet, our eCH4 yields are in the range of 18.5–25.0 g/kg DMI obtained by Gwatibaya et al. (2023) and close to the value of 21.1 g/kg DMI obtained by Gbenou et al. (2023) through direct measurement in West African Fulani zebu bulls fed below their maintenance requirement on dry pasture grass harvested at the end of the growing cycle. Similarly, an eCH4 yield of 18.5 g/kg DMI was obtained by Rendón-Huerta et al. (2018) for rations with a forage share of over 56%.

Our results confirm the seasonal patterns of eCH4 emissions, whereby higher eCH4 production in the wet season can be explained by the higher DMI during this season.

The average EI of lactating cows (g CH4/kg FPCM) did not differ significantly between seasons (70.5 in the dry season and 74.3 in the wet season). Although these results do not agree with those of Feyissa et al. (2023), who considered systems with different production levels, these authors argued that low to medium milk production systems offer a good opportunity for reducing eCH4 levels by increasing milk production through improvements in animal diet quality. In this regard, Somda et al. (2024) suggested the use of specific protein-rich feeds such as leguminous plants or concentrates. They observed low enteric methane emissions and improved milk yields with a higher crude protein (CP) content in cows' diets. Since diet composition has a direct influence on eCH4, CH4 emissions could be reduced by improving feed quality, especially crude protein content (Feyissa et al. 2023). Garg et al. (2018) concurred with these findings and reported that high-quality forages can improve milk yield while reducing EI.

4.3 | Limitations of the Study

Lactation numbers and stages of the cows were not considered in the current study but may have influenced the intensity of enteric methane emissions (Villanueva, Ibrahim, and Castillo 2023). In addition, this study did not distinguish between the different dairy production systems in the study area; it focused on the animal category and season only. Accounting for farm type would have allowed the comparison of eCH4 production across different dairy farming systems in the peri-urban areas of South Benin and the identification of the most climate-friendly farm types to be supported by policies. Another important shortcoming of the current study is the indirect estimation of feed intake in grazing animals. Mimicking the animal's diet selection using the hand-plucking method is difficult, especially in the field conditions of the study area. We acknowledge that this method does not provide the exact quantity of fodder consumed by animals; we therefore only used the collected vegetation samples to determine the nutritional composition of the grazed diet as a basis to estimate DMI and GE, and from there GEI. Reliable feed intake estimates are a key factor in accurately estimating eCH4 emissions in pasture-based production systems (Berdos et al. 2023). Because direct measurement of feed dry matter intake is laborious and expensive, indirect methods using digestive markers could be used instead (Guinguina et al. 2019). However, while using external markers to predict DMI in extensive production systems in sub-Saharan Africa is a reliable method, its application requires careful calibration and validation (Guinguina et al. 2019). Another potential alternative for determining dry matter and nutrient intake in grazing cattle is to estimate feed nutrient content (crude protein and organic matter digestibility) from the animals' daily fecal excretion (Aarons, Gourley, and Powell 2020).

5 | Conclusion

On-farm data coupled with the 2006 IPCC Tier 2 method were used in this study to estimate eCH4 emissions in the peri-urban dairy farming systems of South Benin. Calculated eCH4 values were higher in the wet than in the dry season, and in older than in younger animals. It is therefore essential to accurately estimate DMI on pasture to reduce uncertainties in estimating enteric methane emissions from grazing livestock. Despite these shortcomings, the results of our study indicate that it is possible to reduce enteric methane emissions in the investigated peri-urban dairy production systems by improving the farmers' feeding strategies while simultaneously increasing cow productivity. In particular, dry season supplementation with protein-rich feeds seems to be indicated. To account for the diversity of dairy farm types in the study area, further data collection is needed; particular attention should thereby be paid to farm type differences in herd size, herd structure, and breed composition, as these variables may affect the annual milk output of a farm.

Author Contributions

Fifame Panine Yassegoungbe, Eva Schlecht, Mohamed Habibou Assouma, and Luc Hippolyte Dossa designed the study. Fifame Panine Yassegoungbe, Gaius Segbegnon Vihowanou, and Tawakalitu Onanyemi collected the data. Fifame Panine Yassegoungbe performed statistical analyses and drafted the manuscript. Eva Schlecht, Mohamed Habibou Assouma, and Luc Hippolyte Dossa reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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