Differences in enteric methane emissions across four dairy production systems in the urbanizing environment of an Indian megacity

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Low- and middle-income countries (LMICs) are rapidly urbanizing, leading to a high demand for high-quality animal products. Production increase is seen as a key to meeting this demand and reducing the global environmental impact of low-yielding dairy production system (DPS) often found in LMICs. Therefore, the present study assesses the relationship between enteric methane emissions and different dairy production strategies, taking DPS in the rural–urban interface of Bengaluru, an Indian megacity, as a case study. Twenty-eight dairy farms, evenly distributed across four DPS, were monitored for 1 year (eight visits at 6-week intervals). Following IPCC 2006 guidelines and a Tier 2 approach, enteric methane emissions from dairy cattle were calculated as carbon dioxide equivalents (CO_2 eq). Dairy producers in Ext_{DPS}, an extensive DPS found throughout the rural–urban interface of Bengaluru, fed their dairy cattle a high-quality diet, partly based on organic wastes from markets or neighbors, achieving 9.4 kg energy-corrected milk (ECM) per cow and day. Dairy producers in $Semi-A_{DPS}$, a semi-intensive and rural DPS, fed an average quality diet and achieved the lowest milk production (7.9 kg ECM $cow^{-1} day^{-1}$; $p < 0.05$). Dairy producers in $Semi-B_{DPS}$, another semi-intensive and rural DPS, relied on average quality but more abundant feedstuffs and achieved a production of 10.0 kg ECM $cow^{-1} day^{-1}$. A similar milk yield (10.1 kg ECM $cow^{-1} day^{-1}$) was achieved by Int_{DPS}, an intensive and rural DPS. The intensity of enteric methane emissions was the highest in $Semi-B_{DPS}$ (1.38 kg CO_2-eq kg^{-1} ECM; $p < 0.05$), lowest in Ext_{DPS} (0.79 kg CO_2-eq kg^{-1} ECM; $p < 0.05$), and intermediate in $semi-A_{DPS}$ and Int_{DPS}. The results highlight the close relationship between the intensity of enteric methane emissions and the intensification strategies chosen by dairy producers based on locally available resources. They also underline the importance of region- and system-specific environmental assessments of production systems in LMICs.

1 Introduction

The rapid urbanization in low- and middle-income countries (**LMICs**) over the last decades (United Nations, 2018a) is now a major driver of change in local resources available to dairy producers: on the one hand, urbanization affects land and labor availability since land competition and job opportunities increase as cities grow (Satterthwaite et al., 2010). On the other hand, urbanization, through improved rural–urban linkages, also eases access of dairy producers to inputs such as concentrate feeds and high-yielding cattle genotypes, as well as markets, which are key factors for a production increase (Duncan et al., 2013). Along with the rapid urbanization in West Africa and Asia since the 1990s and driven by urban consumers' demand for daily provision of a highly perishable and nutritionally important product (Schlecht et al., 2019), up to one-third of global milk is now produced by urban and peri-urban dairy production systems (**DPS**) in LMICs (United Nations, 2018a; FAO, 2020). Social-ecological dynamics of urban and peri-urban DPS have been documented in various countries, such as Burkina Faso and Ghana (Dossa et al., 2015; Roessler et al., 2016), Benin (Yassegoungbe et al., 2022), Ethiopia (D'Haene and D'Haese, 2019), Egypt (Daburon et al., 2017), and Bengaluru, India (Reichenbach et al., 2021a). In Bengaluru, the urban and peri-urban space even offers new sources of feedstuffs, such as organic fruit and vegetable wastes from markets or neighbors, and green fodder collected from the surroundings of Bengaluru's numerous urban and peri-urban lakes (Prasad et al., 2019).

In LMICs, milk productivity is usually low and DPS are perceived as having a disproportionately high global environmental impact in comparison to high-yielding DPS because of the strong correlation between emission intensity of greenhouse gases (**GHG**) and production (Gerber et al., 2011, 2013). Enteric fermentation (**EF**) is often the largest contributor to emission intensity of livestock products (Gerber et al., 2013; Ndung'u et al., 2022). Low-yielding DPS, however, have a large mitigation potential, whereby common strategies for production increase often focus on improved feeds, feeding, and animal genetics that increase production while reducing emissions, therefore doubling as mitigation options (Gerber et al., 2013). Diet quality and the genetic makeup of cows are defined through the production strategy chosen by dairy producers according to the resources available to them. In LMICs, resource availability is, however, frequently fluctuating, and especially forage availability, both quantitative and qualitative, can constrain dairy production during the dry season or a drought (Lukuyu et al., 2015). Another major constraint is high ambient temperatures during the dry season and the associated risk of heat stress in dairy cows, which negatively impacts milk production (West, 2003). The challenging dairy production environment in LMICs thus limits the adoption of high-yielding cattle genotypes as part of dairy producers' production strategy because these breeds are often non-native and more susceptible to local environmental constraints (Burrow, 2012).

To assess potential GHG mitigation options in such systems, the present study therefore aims to analyze the relationship between the intensity of enteric methane emissions and farmers' dairy production strategies, taking DPS in the rural–urban interface (**RUI**) of Bengaluru, an Indian megacity, as the case study. Not only is India rapidly urbanizing but it also has the largest dairy herd in the world, characterized, however, by low production. Hence, the contribution of Indian dairy production to global GHG emissions is considered

being disproportionately high but with a large mitigation potential (Gerber et al., 2011, 2013).

In Bengaluru's RUI, four DPS with different production strategies have recently been documented (Reichenbach et al., 2021a). The present study thus asks the following question: Does the intensity of enteric methane emissions of these four Indian DPS that coexist within the same rapidly urbanizing environment differ according to their production strategy? To answer this question, we assessed the intensity of enteric methane emissions per unit of milk produced by four clusters of seven dairy farms each that represented the four DPS within Bengaluru's RUI as documented by Reichenbach et al. (2021a).

2 Materials and methods

2.1 Research area and dairy production systems

Bengaluru is the capital of the southern Indian state of Karnataka and one of the emerging megacities of the recent decades: Its population grew at an average annual rate of 4% between 2000 and 2018 and is currently over 10 million (United Nations, 2018b). Bengaluru has a hot semi-arid climate with a dry season (March–May) followed by the monsoon season (June–October) and winter (November–February). Monthly temperatures range from 18.5°C to 29.5°C and annual rainfall reaches 948 mm (average for 2013–2017, weather station data of the University of Agricultural Sciences Bangalore, GKVK campus). The administrative district of Bengaluru Urban has a bovine population of 145,000 head (National Dairy Development Board, 2015). To assess dairy production strategies in Bengaluru's RUI, two research transects were established along a northern and a southern urban-to-rural gradient (Figure 1; Hoffmann et al., 2017) and 337 dairy farms were surveyed (Reichenbach et al., 2021a). The genotypes found in Bengaluru's RUI included Holstein Friesian (HF, 54% of all cattle in the survey) and Jersey (15%) cattle, further referred to as *exotic* as opposed to *native* genotypes (10%; mostly *Bos indicus* Hallikar, a draught breed from the State of Karnataka). Crossbreeds (21%) were either (i) exotic × exotic (first generation), (ii) exotic × native (first generation), or (iii) multi-generation crosses.

Across the 337 surveyed dairy farms, Reichenbach et al. (2021a) identified four DPS based on their spatial distribution within Bengaluru's RUI, their feeding strategy, and herd management (Table 1). The first was a DPS found along the whole RUI of Bengaluru and named as Ext$_{DPS}$ because of the dairy producers' minimum expenditure in labor and capital. In Ext$_{DPS}$, dairy cattle were sent to pasture and fed forages that were not produced on the dairy farm: Some forages were bought but were more often collected from public grounds or markets such as discarded fruits or vegetables, further referred to as organic wastes. Most dairy producers in Ext$_{DPS}$ kept herds with exotic cattle next to crossbreeds or native ones. The production strategy of Ext$_{DPS}$ was most obviously impacted by urbanization as their reliance on external resources, such as organic wastes and public grounds for pasture, was a direct adaption strategy to the dwindling availability of agricultural land to cultivate forages (Reichenbach et al., 2021a). Two semi-intensive DPS were found in rural areas; in both, dairy cattle were sent to pasture and fed forages produced on the dairy farm. However, these two DPS differed in their
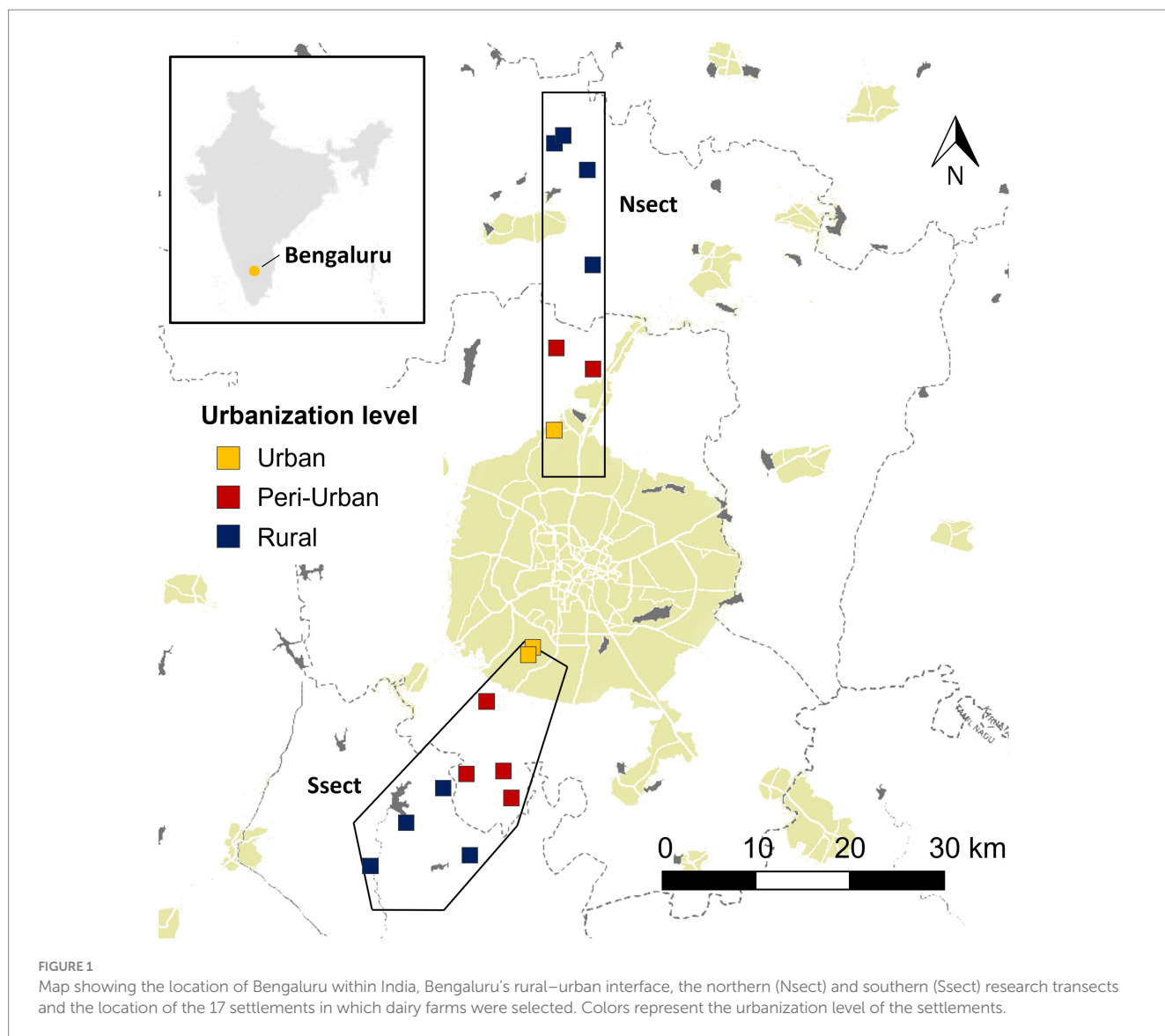
FIGURE 1
Map showing the location of Bengaluru within India, Bengaluru's rural–urban interface, the northern (Nsect) and southern (Ssect) research transects and the location of the 17 settlements in which dairy farms were selected. Colors represent the urbanization level of the settlements.

TABLE 1 Classification criteria and main characteristics of the four dairy production systems (DPS) within Bengaluru's rural–urban interface.

| | | Production strategy | | | |
| | | Feeding | | Breeding | |
DPS	Spatial distribution	Self-cultivated forages	Access to pasture	Genotype kept	Herd management
Ext_{DPS}	Urban to rural	No	Yes	Exotic + Crossbreed	Mixed
$Semi\text{-}A_{DPS}$	Rural	Yes	Yes	Exotic	Closed
$Semi\text{-}B_{DPS}$	Rural	Yes	Yes	Exotic + Crossbreed	Dynamic
Int_{DPS}	Rural	Yes	No	Exotic	Mixed

The four DPS coexisting in Bengaluru's rural–urban interface are: Ext_{DPS} = ubiquitous extensive; $Semi\text{-}A_{DPS}$ = rural semi-intensive, variant A; $semi\text{-}B_{DPS}$ = rural semi-intensive, variant B; Int_{DPS} = rural intensive. "Exotic" includes Holstein Friesian and Jersey genotypes. The classification criteria "herd management" categorized each herd as follows: a herd with no cattle inflow or outflow was classified "closed," a herd with cattle inflow or outflow, or both, as "dynamic." DPS in which both types of herd management were followed by dairy producers were classified as "mixed."

breeding strategy: in Semi-A$_{DPS}$, dairy producers kept mostly exotic cattle and for replacement relied on dairy cattle born on farm. By opposition, in Semi-B$_{DPS}$, most dairy producers kept mixed genotypes and had dynamic herd management with frequent buying, selling, or both, of dairy cattle. These two DPS were characterized as semi-intensive because of the dairy producers' higher expenditure on labor and capital, i.e., forage cultivation and high-yielding genotypes. Located in rural areas was the most intensive DPS named Int$_{DPS}$, in which dairy cattle were not sent to pasture but fed exclusively on-farm with self-cultivated forages. Most dairy producers in Int$_{DPS}$ kept herds

with exotic cattle only. Dairy producers in this DPS therefore had the highest labor and capital expenditure of all four DPS. Located in the immediate rural periphery of the city, the latter three DPS benefited from the network of dairy cooperatives and improved rural–urban linkages throughout Greater Bengaluru: established to supply the demand of urban consumers, it provided rural dairy producers with easier access to markets and production inputs, notably concentrated feeds and exotic genotypes, thereby supporting an increase in dairy production (Reichenbach et al., 2021a).

2.2 Data collection

Twenty-eight dairy farms, seven per DPS, were selected from the 337 farms surveyed in Bengaluru's RUI (Supplementary Table S1) and visited eight times at 6-week intervals over 1 year (June 2017 to May 2018). Figure 1 shows the location of the 17 settlements from which dairy farms were selected. Dairy cattle on each farm were categorized as either lactating cow, dry cow (not lactating, pregnant, or not pregnant), heifer (pregnant or inseminated at least once), young cattle, and calf (<3 months old). Non-productive cattle refers to all categories of cattle except lactating cows. Focusing on the feeding strategy of the dairy farm, the variables quantified at each visit for each dairy cattle followed Schlecht et al. (2019) and included 24h feedstuff offer (considered equivalent to daily feed intake on the farm as refusals were often difficult to quantify due to feeding practices), pasture time, nutritional value of per-farm samples of all offered feedstuffs, concentrations of dry matter (DM), digestible organic matter determined *in vitro* (DOM) and therefrom derived metabolizable energy (ME; Menke et al., 1979), crude protein (CP), neutral detergent fiber (NDF) and acid detergent fiber (ADF); analysis of 321 representative feed samples (see Supplementary Table S2 for average quality of feedstuffs), daily milk production (kg milk $cow^{-1} day^{-1}$ = daily milk offtake + correction for direct calf consumption based on indirect calf consumption records; Reichenbach et al., 2021b), fat and protein content of milk (Lactoscan Milk Analyzer, Softrosys Technologies, Bengaluru, India), and heart girth of the animal (HG; in cm). Gross energy intake (GE) was calculated from ME intake according to Hales (2019). Feed intake at pasture was estimated from actual grazing time manually observed on pasture and an intake rate of 8 g DM per kg metabolic weight and hour (Ayantunde et al., 2002; Reichenbach et al., 2021b). DOM of pasture biomass was based on the analysis of 32 representative samples of non-cultivated grasses (collected by dairy producers from public grounds for on-farm feeding) in urban areas where cows had also access to organic household or market wastes dumped in the streets and three representative samples of vegetables and fruit mixes. Individual body weight (BW), metabolic weight, and daily weight gain (Δ kg BW day^{-1}), were calculated based on an HG to BW regression (kg BW = 3.867 + 2.98 × log10 (HG); 569 weight records; R2 = 0.9846; Grund, 2018; see Supplementary Table S3 for body weight and daily weight gain values). The date of last calving was asked for each cow at the first visit and new calving dates were recorded during the monitoring year. Dry period and lactation duration were calculated as averages for each DPS.

Using the same dataset, Reichenbach et al. (2021b) had calculated ME and CP supply levels (undersupplied, adequately supplied, and oversupplied) for lactating cows, dry cows, and heifers. The supply levels of ME and CP were comparable and followed a similar pattern, i.e., lactating cows, dry cows, and heifers in Ext_{DPS} were adequately

supplied on average, but there was a wide variation from animal to animal. In contrast, there was adequate to oversupply in the three other DPS. Interestingly, regardless of DPS, lactating cows were on average adequately supplied, while dry cows and heifers were almost systematically oversupplied.

2.3 Computation of livestock-related greenhouse gas emissions

Following the IPCC (2006) guidelines and a Tier 2 approach, livestock-related GHG emissions per unit of milk were calculated for each dairy farm in CO_2-eq of CH_4 (28 kg CO_2-eq kg^{-1} CH_4) from EF. To account for the herd management strategy of each DPS, the calculated emission intensity included the CH_4 emissions due to enteric fermentation of all lactating cows and non-productive cattle, and therefore, consolidated at the farm level, all emissions were first calculated per cattle based on its diet. Our calculations were based on 855 nutritional and 478 production records from 147 dairy cattle. The emission intensity factor related to enteric fermentation was calculated based on the IPCC equation 10.21 using the standard methane conversion factor Ym = 6.5%. The functional unit to which all emissions were allocated was 1 kg of energy-corrected milk (ECM; 1 kg ECM = kg milk × (0.25 + 0.122 fat % + 0.077 protein %); Sjaunja et al., 1990). CH_4 emissions, milk production, and intensity of enteric methane emissions per unit of milk were first calculated per visit, with each visit representing a 42-day cycle. Multiple visits per dairy farm during the same season (from one visit to a maximum of four) were considered as repeated measurements ($n_{individual}$ = 214; $n_{repeated}$ = 82). CH_4 emissions, milk production, and intensity of enteric methane emissions in CO_2-eq per unit of milk were then calculated per year (n = 24); four dairy farms, one per DPS, were excluded because they stopped dairy production during the monitoring year.

2.4 Statistical analysis of results

All variables (Y) were analyzed using linear mixed-effects models (lmer) followed by *post hoc* pairwise comparison (Bonferroni adjustment) in R (RStudio version 4.2+). In the main model, dairy farm nested in season was included as a random effect to correct for repeated measurements: $Y_{ij} = DPS_i + farm:season_j + e_{ij}$.

Thereby, DPS comprises factors such as cattle genotype, herd management, feeding strategy, and location (Table 1; see Reichenbach et al., 2021a for details). Results are presented as arithmetic mean and standard deviation (±), unless specified otherwise. Significance was declared at a *p*-value of <0.05 for all analyses. As the number of dairy cattle varied within and between farms at each visit and thus season, cumulative numbers per DPS and visit are presented in Supplementary Table S4.

3 Results

3.1 Characteristics of dairy farms

A dairy herd within Bengaluru's RUI typically included 2 ± 1.2 lactating cows (n = 28). The number of non-productive dairy cattle,

however, differed between DPS, with dairy producers in Semi-B$_{DPS}$ having larger herds than any other DPS (3 ± 2.0 additional non-productive dairy cattle; $p < 0.05$; Table 2). Lactating cows in Ext$_{DPS}$ had an intermediate average milk yield and protein content (9.4 kg ECM cow^{-1} day^{-1} with 3.10% protein) and were milked longer (414 days) than cows in any other DPS (Table 2). The most productive cows were found in Semi-B$_{DPS}$ (10.0 kg ECM cow^{-1} day^{-1} on average) and in Int$_{DPS}$ (10.1 kg ECM cow^{-1} day^{-1} on average; lactation length of 356 days for both DPS), with the latter also having a higher milk protein content (3.12%). Milk yield in Semi-A$_{DPS}$ was the lowest (7.9 kg ECM cow^{-1} day^{-1} on average; $p < 0.05$), with a protein content of 3.02% and a lactation length of 359 days. Yearly milk production per farm averaged 5,684 kg ECM in Semi-A$_{DPS}$, 6,353 kg ECM in Ext$_{DPS}$, 9,399 kg ECM in Int$_{DPS}$, and 10,079 kg ECM in Semi-B$_{DPS}$ (Table 2).

3.2 Quality of feedstuffs and diets

Common green forages (27% DM) fed in Bengaluru's dairy farms included African tall maize (*Zea mays* L.), hybrid Napier grass (*Pennisetum glaucum × P. purpureum*), and a wide range of wild (non-cultivated) grasses collected from public grounds and, in urban and peri-urban areas, from the surroundings of Bengaluru's numerous lakes. Green forages had a DOM of 59% and contained 16.7 MJ GE kg^{-1} DM. On average, green forage contributed to more than half of the daily dry matter intake (DMI) of dairy cattle during the monsoon season (Figure 2). However, the availability of green forages decreased during winter and especially in the dry season, leading to an increased dietary share of dry forages (90% DM) during these two seasons. Dry forages were commonly straw of finger millet (*Eleusine coracanal* L., locally referred to as ragi) and occasionally dried maize (straw without cobs). Dry forages were rich in fiber (708 g NDF kg^{-1} DM). At 54%, DOM of dry forages was therefore the lowest of all types of feedstuffs, and their average GE content was 16.5 MJ kg^{-1} DM. Organic wastes (21% DM) – carrot tops, vegetable or fruit wastes from markets, fields, or neighbors – were fed mostly by dairy producers in Ext$_{DPS}$ and of good nutritional value (68% DOM, 17.3 MJ GE kg^{-1} DM). Dairy producers also used a large variety of commercial concentrate feeds (89% DM): wheat flour, with or without bran, corn flour, pelleted commercial feed, chickpea husks (*Cicer arietinum* L., referred to as Bengal gram), and groundnut cake. They offered these concentrate feeds individually or mixed several ones and usually added salt or a

commercial mineral mixture. Overall, concentrate feeds had the highest DOM (77%) and GE content (17.6 MJ kg^{-1} DM) among all types of feedstuffs. The contribution of concentrate feeds to daily DMI of dairy cattle was constant across seasons (Figure 2). Generally, lactating cows received the highest share of concentrate feeds, followed by dry cows and heifers (Supplementary Table S5). The nutritional value of biomass ingested during pasturing was similar to the one of green forages (58% DOM, 16.8 MJ GE kg^{-1} DM). However, the nutritional value of biomass ingested during pasturing in urban areas was higher than in peri-urban and rural areas (68% DOM, 17.3 MJ GE kg^{-1} DM) because it also included organic wastes, to which cows had access in the streets. During the dry season, there was a small but significant drop in the contribution of pasture biomass to daily DMI (Figure 2).

Despite differences between dairy producers in the use of feedstuffs and seasonal variation in the contribution of different types of feedstuffs to total daily DMI, there were few differences in average diet DOM (Table 3). Season affected the average diet DOM of Ext$_{DPS}$, which was lower in the winter than in the dry season ($p < 0.05$). During the dry season and the monsoon, the average diet DOM of Ext$_{DPS}$ was also higher than in any other DPS ($p < 0.05$). Details on diet quality (weighted average DOM), feedstuffs' contribution (%) to DMI and daily DMI (kg DM cattle^{-1} day^{-1}) per category of dairy cattle and DPS are given in Supplementary Table S5.

3.3 Livestock-related emissions of dairy production systems

3.3.1 Enteric methane emissions

The amount of enteric methane that was released per dairy farm over a 42-day cycle was impacted by DPS: at all times, emissions were high in Semi-B$_{DPS}$ and low in Ext$_{DPS}$ as well as Semi-A$_{DPS}$, while intermediate values were obtained for Int$_{DPS}$ (Table 4).

3.3.2 Intensity of enteric methane emissions per unit of milk and per DPS

Despite variations within and between DPS (Figure 3), there was no significant difference in intensity of enteric methane emissions per unit of milk over a 42-day cycle milk due to the large variation within all DPS except Semi-A$_{DPS}$. Interestingly, there was a trend of Semi-B$_{DPS}$ to (negatively) impact emission intensity ($p = 0.06$).

TABLE 2 Main characteristics of dairy farms ($n = 28$) per dairy production system (DPS) within Bengaluru's rural−urban interface.

DPS	Dairy cattle (*n*)		Daily DMI (kg DM cow^{-1})	Milk production				
	Lactating cow	Non-productive		Dry period (days)	Lactation (days)	Protein content (%)	Daily production (kg ECM cow^{-1})	Total production (kg ECM dairy farm^{-1} year^{-1})
Ext$_{DPS}$	2	1[a]	10.9[a]	85	414	3.10[ab]	9.4[a]	6,353
Semi-A$_{DPS}$	2	2[a]	11.5[a]	91	359	3.02[a]	7.9[b]	5,684
Semi-B$_{DPS}$	3	3[b]	13.5[c]	77	356	3.07[ab]	10.0[a]	10,079
Int$_{DPS}$	2	2[a]	15.7[d]	78	356	3.12[b]	10.1[a]	9,399
SEM	0.1	0.2	0.59	–	–	0.033	0.63	864.3

DM, dry matter; DMI, dry matter intake; ECM, energy-corrected milk; SEM, standard error of the mean. Values within a column with different superscript letters differ significantly at $p < 0.05$. The four DPS coexisting in Bengaluru's rural–urban interface are Ext$_{DPS}$ = ubiquitous extensive; Semi-A$_{DPS}$ = rural semi-intensive, variant A; Semi-B$_{DPS}$ = rural semi-intensive, variant B; Int$_{DPS}$ = rural intensive. In this table, "cow" refers exclusively to lactating cows. Daily DMI for non-productive dairy cattle are available in Supplementary Table S5.
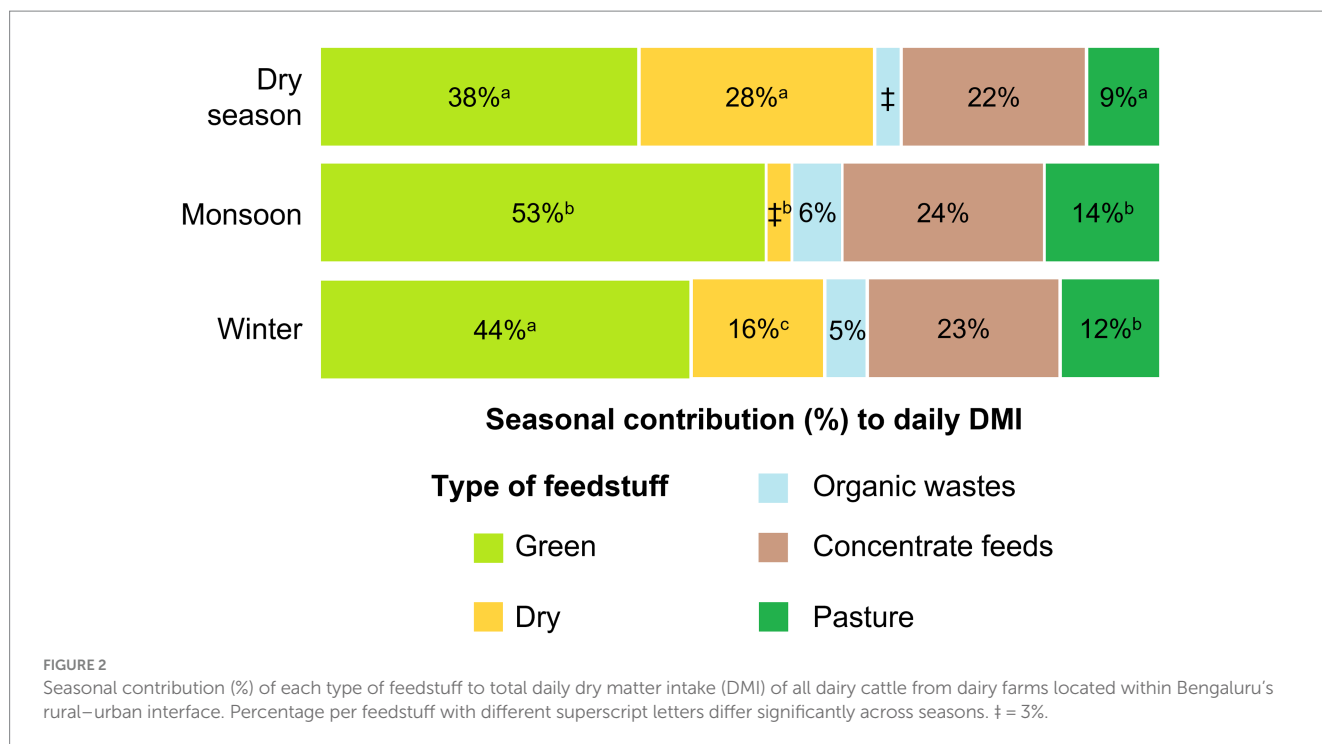
FIGURE 2
Seasonal contribution (%) of each type of feedstuff to total daily dry matter intake (DMI) of all dairy cattle from dairy farms located within Bengaluru's rural−urban interface. Percentage per feedstuff with different superscript letters differ significantly across seasons. ‡ = 3%.

TABLE 3 Seasonal variation in diet quality based on the weighted average digestible organic matter (DOM, %) per dairy production system (DPS) within Bengaluru's rural−urban interface.

DPS	Diet quality (weighted average DOM, %)		
	Dry season	Monsoon	Winter
Ext_{DPS}	70[a A]	68[a AB]	66[B]
Semi-A_{DPS}	66[b]	64[b]	65
Semi-B_{DPS}	65[b]	64[b]	64
Int_{DPS}	65[b]	65[b]	64
SEM	0.4	0.4	0.3

Values with different lowercase (DPS) or capital (season) superscript letters differ significantly at $p < 0.05$. The four DPS coexisting in Bengaluru's rural–urban interface are Ext_{DPS} = ubiquitous extensive; Semi-A_{DPS} = rural semi-intensive, variant A; Semi-B_{DPS} = rural semi-intensive, variant B; Int_{DPS} = rural intensive.

TABLE 4 Amount of methane (CH_4) emitted due to enteric fermentation (EF) expressed in carbon dioxide equivalents (kg CO_2-eq) over a 6-week period (42-day cycle) for each dairy production system (DPS) in Bengaluru's rural−urban interface.

DPS	Amount of CH_4 emissions due to EF in 42 days (kg CO_2-eq)
Ext_{DPS}	809[a]
Semi-A_{DPS}	709[a]
Semi-B_{DPS}	1224[b]
Int_{DPS}	1007[ab]
SEM	42.7

Within the column, values with different superscript letters differ significantly at $p < 0.05$. The four DPS coexisting in Bengaluru's rural–urban interface are Ext_{DPS} = ubiquitous extensive; Semi-A_{DPS} = rural semi-intensive, variant A; Semi-B_{DPS} = rural semi-intensive, variant B; Int_{DPS} = rural intensive.

The yearly intensity of enteric methane emissions confirmed this tendency, with Semi-B_{DPS} having a significantly higher intensity of enteric methane emissions per unit of milk (1.38 kg CO_2-eq kg^{-1} ECM) than Ext_{DPS} (0.79 kg CO_2-eq kg^{-1} ECM; $p < 0.05$; Figure 4). Intermediate intensities were calculated for Semi-A_{DPS} (1.04 kg CO_2-eq kg^{-1} ECM) and Int_{DPS} (1.21 kg CO_2-eq kg^{-1} ECM).

4 Discussion

Quantifying the emission intensity of enteric methane per unit of milk from Bengaluru's DPS provides interesting insights into its relationship with the production strategies chosen by dairy producers based on the resources available to them within the RUI of an emerging megacity. In particular, two findings are interesting: (a) during a 42-day cycle, variation within all DPS except Semi-A_{DPS} was

large, indicating potential for mitigation of emissions at the farm level; (b) on an annual basis, differences in emission intensities existed, but were relatively small, even non-existent, despite different production strategies.

The production strategies adopted by Bengaluru's DPS were primarily based on feeding management, namely, reliance on self-cultivated forages or pasture use or both, implying that dairy producers not sending their cattle to pasture required more means of production (land and labor) for their activity, while the others took advantage of local resources available for free or at a cheap price (organic wastes, green forages from public grounds; Reichenbach et al., 2021a). Based on DOM data, feeding strategies across Bengaluru's DPS can roughly be distinguished as follows: feeding a good quality diet and using pasture (Ext_{DPS}), feeding an average quality diet and using pasture (Semi-A_{DPS}), or oversupplying a diet of average quality, with or without using pasture (Semi-B_{DPS} and Int_{DPS}). The
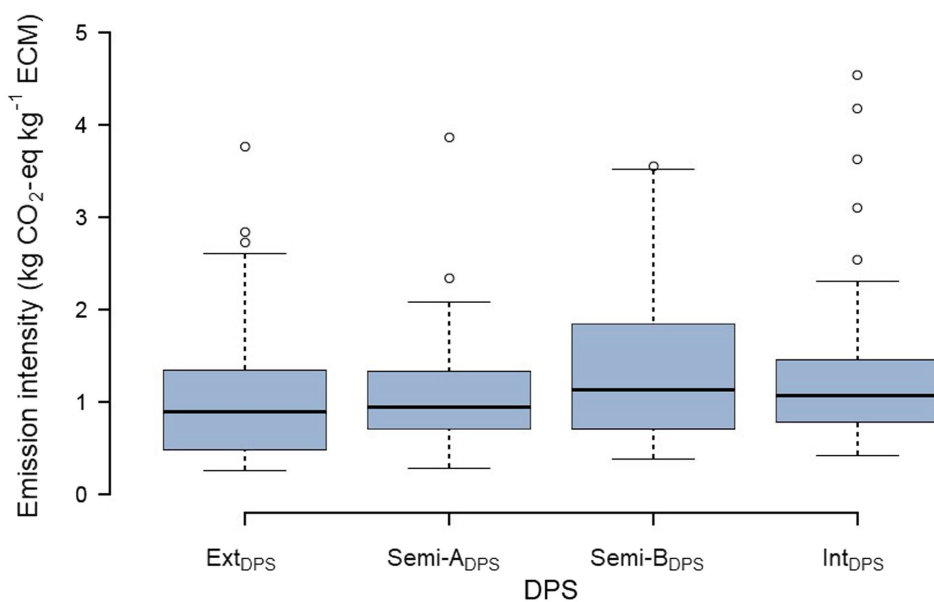
FIGURE 3
Intensity of enteric methane emissions, expressed as carbon dioxide equivalents (CO_2-eq) per kg of energy corrected milk (ECM), during a 6-week period per dairy production system (DPS) within Bengaluru's rural–urban interface. The four DPS coexisting in Bengaluru's rural–urban interface are Ext_{DPS} = ubiquitous extensive; $Semi-A_{DPS}$ = rural semi-intensive, variant A; $Semi-B_{DPS}$ = rural semi-intensive, variant B; Int_{DPS} = rural intensive.
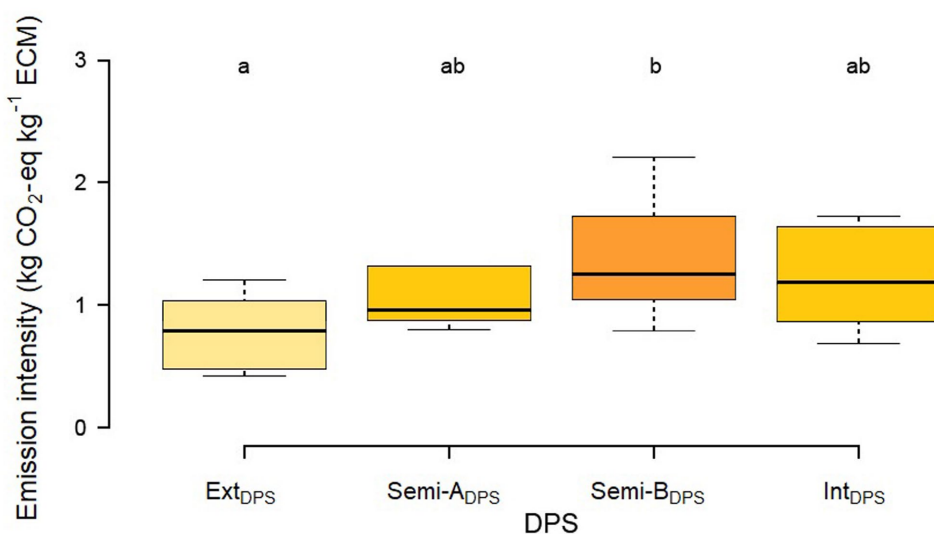

FIGURE 4
Intensity of enteric methane emissions, expressed as carbon dioxide equivalents (CO_2-eq) per kg of energy corrected milk (ECM) during 1-year period per dairy production system (DPS) within Bengaluru's rural–urban interface. Boxplots with different superscript letters differ significantly across DPS. The four DPS coexisting in Bengaluru's rural–urban interface are: Ext_{DPS} = ubiquitous extensive; $Semi-A_{DPS}$ = rural semi-intensive, variant A; $Semi-B_{DPS}$ = rural semi-intensive, variant B; Int_{DPS} = rural intensive.

production strategy of Ext_{DPS} resulted in the lowest intensity of enteric methane emissions per unit of milk for this most extensive DPS, which was extensive in its use of labor and capital (Reichenbach et al., 2021a), as well as conventional forages (Reichenbach et al., 2021b) but relied on atypical feedstuffs (banana peel, cabbage leaves, and field bean leaves) of good quality in addition to concentrate feeds, that were also used in all other DPS. Although energy and crude protein supply

to the animals were variable and frequently implied undersupply of dairy cows, at system-level Ext_{DPS} had the best feed conversion efficiency among Bengaluru's four DPS (Reichenbach et al., 2021b). At the same time, Ext_{DPS} was also relying the most on cheap but external resources. Whereas reliance on external inputs is a common characteristic of intensive DPS in high-income countries, in Bengaluru, reliance on external inputs was the result of a production

strategy based on the highly flexible use of several locally available low-cost but quality feed resources by dairy producers as an adaptation to their urbanizing environment and the subsequent decrease of land and labor availability. In consequence, for Bengaluru's Ext$_{DPS}$, the reliance on external resources was not a limiting factor for milk production but an enabling one: without access to organic wastes or green forages on public grounds, dairy producers in Ext$_{DPS}$ would have to stop their activity. At this stage of knowledge, it is interesting to note that such a production strategy can exist as a complement to more "traditional" strategies to increase production without leading to too large a difference in emission intensity, and can even have a favorable outcome. Therefore, the consequences of such a strategy, for the longer-term economic sustainability or rather, vulnerability, of the DPS, the scalability of such a minimal expenditure strategy, as well as for its upstream emissions need to be further investigated.

The semi-intensive and intensive strategies of Semi-B$_{DPS}$ and Int$_{DPS}$ resulted in an oversupply of their cattle with feed (Reichenbach et al., 2021b), and their intensity of enteric methane emissions per unit of milk was thus crippled by "unnecessary" CH$_4$ emissions. National emission intensities computed according to IPCC (2006) are usually based on estimated daily DMI derived from national dairy cattle requirements and average diet (quality). In view of feeding inefficiencies previously quantified in Bengaluru's RUI (Reichenbach et al., 2021b), the environmental impact of Bengaluru's DPS based on estimated DMI would potentially differ from the present computations that are largely based on quantified DMI (Goopy et al., 2018). This underlines the importance of detailed assessments of ruminant production systems in LMICs, which might emit less greenhouse gasses than projected by gross assessments based on literature (Goopy et al., 2018).

To a lesser extent, the production strategy of Bengaluru's DPS also relied on breeding management, namely, the use of exotic genotypes and cattle inflow and outflow within the herd (Reichenbach et al., 2021a). Crossbreeding of local genotypes with high-yielding exotic genotypes is a common strategy in tropical countries to increase production (Widi et al., 2015), which potentially decreases emission intensity due to the general relationship between (increasing) production at the cow level and (decreasing) emission intensity as highlighted by Gerber et al. (2011). In the case of smallholder beef production in central Java, Indonesia, the global environmental impact of farms with crossbred animals was however similar to those with unimproved cattle: The productivity gain due to crossbreeding was offset by the additional emissions related to the additional feed resources needed to fatten the crossbreds (Widi et al., 2015). In the context of Bengaluru, no direct relationship between cattle genetics and intensity of enteric methane emissions could be detected between systems keeping mixed herds and those keeping mostly exotic cows. Inadequate feeding (Reichenbach et al., 2021b), indiscriminate crossbreeding, and heat stress are common in Bengaluru's RUI (Pinto et al., 2020), thus potentially hindering the full expression of exotic genotypes' production potential and limiting breeding as a strategy for production increase. Dairy producers in Semi-B$_{DPS}$ tended to buy and sell dairy cattle at a higher rate than producers in other DPS and kept a higher number of unproductive dairy cattle (Reichenbach et al., 2021a), which contributed to the large variation in emissions from one visit to the next and a higher intensity of enteric methane emissions.

5 Conclusion

Given the observed variability in feed availability, both quantitative and qualitative, across DPS, better feeding strategies are a promising mitigation option for Bengaluru DPS, i.e., providing feed in adequate quantity and quality according to the expected requirements of dairy cattle in a consistent manner (Hermansen and Kristensen, 2011). Targeted feeding would promote animal welfare and resource efficiency, reduce the intensity of enteric methane emissions, and improve the rearing of female offspring on the farm by reducing the age at first calving. Using the network of dairy cooperatives, information on feed quality and dairy cow requirements could be easily disseminated to a large number of smallholder dairy farmers. In the longer term, mitigation options should take a broader system approach, e.g., addressing low reproductive rate and genetic production potential in parallel. Bengaluru's case study sheds light on DPS in a rapidly urbanizing environment with minor differences in emission intensities depending on the production strategy chosen by the dairy producers, which is largely based on the locally available resources. The study thus contributes to the still limited but growing body of literature on the environmental impacts of livestock production systems in urbanizing regions of India, with strong parallels to similarly transforming regions across the LMICs. Given that millions of small-scale producers in LMICs are suspected of contributing disproportionately to global dairy GHG emissions, this study highlights the importance of a careful local assessment of system-specific GHG emissions, as dairy farms could be more emission-efficient than assumed, even at intermediate levels of production and with the implementation of a limited set of strategies to increase production. The local perspective therefore also challenges the case for a unique pathway to emission mitigation in LMICs. Despite different production strategies, emission intensities varied little between DPS, highlighting that diverse production strategies can be environmentally friendly when based on locally available feed resources such as, in India, forages on public grounds or organic wastes, which can contribute to more sustainable livestock production in the context of circular food systems.

Data availability statement

All relevant data used to calculate the intensity of enteric methane emissions for different dairy production systems in Bengaluru are presented in detail in the article and the supplementary material; further data requests can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for this animal study because all data were collected from dairy cows without directly disturbing them (monitoring feed offer and pasturing) and as part of the normal operation of the dairy farm, such as milk production. Only heart girth was measured with a tape directly on the cow, which caused little discomfort to the cow. Each dairy farmer's oral consent to participate with his/her cows in our study was obtained before the start of the 1-year monitoring period and renewed at each visit. Oral consent was preferred to written consent because of the low literacy level of some dairy producers.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1204218/full#supplementary-material

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