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Comparative carbon footprint assessment of milk production from crossbred cattle using life cycle assessment in Eastern and Western Haryana

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Abstract
This study quantified the carbon footprint of milk production from crossbred cattle farms in Haryana using Life Cycle Assessment (LCA) with a “cradle-to-farm gate” system boundary. A field survey was conducted on 32 farms across eight districts, categorized into Eastern and Western regions, using semi-structured interviews to collect data on feeding, management, and input use. Carbon footprints and emission intensity (Ei) per kilogram of fat and protein corrected milk (FPCM) were estimated for each farm. While no statistically significant differences ($p<0.05$) were observed between the regions, farms in the Western region exhibited numerically lower carbon footprints. Enteric methane emissions were identified as the major contributor to greenhouse gas emissions, followed by emissions from fertilizer application and electricity consumption. The study highlights key environmental hotspots in dairy production and provides valuable insights for targeted mitigation strategies.

Keywords: Enteric fermentation, GHG emission, GWP, LCA, methane, nitrous oxide

1. Introduction
The livestock sector is a vital component of global food systems, providing essential nutrition and livelihoods, yet it is also a significant source of greenhouse gas (GHG) emissions. Milk production contributes notably to these emissions, primarily through enteric fermentation, feed production, manure management, and on-farm energy use. Accurately quantifying these emissions is critical for identifying environmental hotspots and implementing effective mitigation strategies.
Life Cycle Assessment (LCA) has emerged as a robust framework for evaluating the environmental impact of dairy systems, offering a “cradle-to-farm gate” perspective that captures emissions from all inputs and processes leading to milk production. Studies indicate that enteric methane is the dominant emission source, followed by emissions associated with fertilizers and electricity use. The emission intensity of milk varies widely with farm management practices, feeding strategies, and regional conditions.
In India, crossbred cattle are extensively reared across diverse agro-climatic zones, yet comprehensive data on their carbon footprint remain limited. Regional assessments are essential to inform context-specific mitigation strategies and improve sustainability in dairy production.
In this study, the carbon footprint and emission intensity of milk production were quantified for crossbred cattle farms in Eastern and Western Haryana. Data from 32 farms, collected through semi-structured interviews, were analyzed using LCA. The study aims to identify key emission sources, compare regional differences, and provide actionable insights for reducing the environmental impact of dairy production while maintaining productivity.

2. Materials and Methods
2.1 Study Area and Farm Selection
The study was conducted on 32 crossbred cattle farms across eight districts of Haryana, India, representing Eastern (Karnal, Sonipat, Yamuna Nagar, Palwal) and Western (Hisar, Sirsa, Bhiwani, Rewari) regions.

Each zone included 16 farms, with four farms per district, to capture regional variations in dairy management.

2.2 Data Collection

Data were collected through semi-structured interviews with farmers and recorded monthly over one year. Information included herd size and composition (age, weight, and physiological stage), total milk production, feed and dry matter intake (DMI), fertilizer use for fodder cultivation, electricity consumption (fodder chopping, concentrate preparation, irrigation, water supply, and lighting), and diesel usage (fodder transport, dung disposal, and other operations).

2.3 Greenhouse Gas Estimation

GHG emissions, including enteric methane, methane from dung, and nitrous oxide from fertilizers, electricity, and diesel use, were calculated using default emission factors established under Indian conditions. Emissions were quantified within a Life Cycle Assessment (LCA) framework with a "cradle-to-farm gate" boundary to estimate carbon footprint and emission intensity per kilogram of fat and protein corrected milk (FPCM).

2.3.1 Computation of GHGs emissions from different activities on farm for production of one kg FPCM

For computing GHGs emission, from different activities in farm for production of 1 kg FPCM by using country specific emission factors, which were estimated at NDRI during feeding trial, were used.

- Enteric CH_4 for different physiological stage of crossbred cattle were estimated by multiplying emission factors (EF) estimated from earlier defined emission factors for Indian conditions (Mohni and Singhal, 2010) [7] based on dry matter intake.
- Manure CH_4 and N_2O emissions were calculated by multiplying dung weight with country specific EF reported by Gupta *et al.* (2007) [5].
- Annual GHGs emission from diesel was calculated by using (2.7 kg CO_2eq/liter diesel) reported by Guideline for voluntary cooperate GHG Reporting (2015) for India.
- Annual GHGs emission from electricity was calculated by using emission factor (1.27 kg CO_2eq. GHGs emission/kWh) reported by "for Haryana, India.
- Annual GHGs emission from chemical fertilizers were calculated by using emission factors (7.41kg CO_2eq/kg urea and 6.47kg CO_2eq/kg DAP) reported by Kool *et al.* (2012) [6].

2.3.2 Impact assessment

Impact assessment explains environmental impact of product of interest. All three main GHGs (CO_2, CH_4 and N_2O) were measured in terms of reference gas CO_2 by using characterization factors to determine the global warming potential of one kg fat protein corrected milk (FPCM)

Total GHGs emission (TGE) = $\sum$ kg CO_2-eq (all sources)

Calculation of Global warming potential (GWP) of GHGs and was expressed as CO_2-equivalents using GWP of different gases given in IPCC, (2013).

$CO_2 = 1$, $CH_4 = 25$ and $N_2O = 298$

$CO_2 = 1$, CH_4 as 28 and N_2O as 265 (IPCC, 2013)

The results are expressed in terms of CO_2 equivalent per functional unit (FPCM) for crossbred cattle farms over a one-year period. Greenhouse gas (GHG) emissions from all relevant sources were quantified for the production of 1 kg of FPCM.

3. Results & Discussion

3.1 Milk yield, fat and protein corrected milk (FPCM) and livestock unit (LU) from eastern and western zones of Haryana

The annual milk yield (litres/year), Fat and Protein Corrected Milk (FPCM, litres/year), and Livestock Units (LU) in the eastern and western zones of Haryana are presented in Table 1. The annual FPCM recorded in the eastern and western zones was 103,948.84 litres and 92,928.39 litres, respectively. Similarly, the annual livestock units were 404.11 in the eastern zone and 379.18 in the western zone. Statistical analysis revealed no significant difference (p<0.05) between the two zones in terms of milk yield, FPCM, and LU. However, numerically higher values for milk yield, FPCM, and LU were observed in the eastern zone compared to the western zone, which may be attributed to the presence of a greater number of productive animals in the eastern region.

3.2 GHGs emissions from eastern and western zones of Haryana

Livestock is a major contributor to greenhouse gas (GHG) emissions, primarily through enteric fermentation, manure management, and the use of electricity, fertilizers, and diesel. Among these, enteric fermentation consistently accounts for the largest share of total GHG emissions from milk production at individual farms (FAO, 2013) [12]. The annual estimated GHG emissions from various activities on crossbred cattle farms in the eastern and western zones of Haryana are presented in Table 2.

3.2.1 Enteric methane emission from eastern and western zones of Haryana

The total CO_2 equivalent emissions from enteric fermentation in the eastern and western zones of Haryana were 85,683.46 and 75,753.54, respectively, as shown in Table 2. The results indicated no statistically significant difference in enteric emissions between the two zones. However, the eastern zone recorded numerically higher emissions compared to the western zone, which can be attributed to the presence of larger farms that tend to be more productive and consequently generate greater enteric emissions. Similar findings were reported by Gerber *et al.* (2011) [3], who demonstrated that higher-producing animals have larger metabolic body sizes and consume more dry matter intake (DMI), leading to increased enteric emissions. Additionally, Thoma *et al.* (2013) [11] and Tubiello *et al.* (2013) [12] observed that large-scale farms are associated with higher greenhouse gas emissions.

3.2.2 Emission from fertilizers use from eastern and western zones of Haryana

The total CO_2-equivalent emissions from fertilizer use in the eastern and western zones of Haryana were 22,523.72 and 19,653.81, respectively, as presented in Table 2. Fertilizer emissions were found to be relatively similar between the two zones; however, the eastern zone exhibited numerically higher emissions compared to the western zone. This increase can be attributed to the extensive cultivation of fodder crops for animal feeding in the eastern region. Additionally, the use of fertilizers in these fields exceeded the recommended levels, thereby contributing to a higher share of emissions from the eastern zone. Similar findings were reported by Gollnow *et al.* (2014) [4] and Gerber *et al.* (2013) [3].

3.2.3 Emission from electricity use from eastern and western zones of Haryana

The total CO_2-equivalent emissions from fertilizer use in the eastern and western zones of Haryana were 22,523.72 and 19,653.81, respectively, as presented in Table 2. Similar values were observed between the two zones. However, the eastern zone recorded numerically higher fertilizer emissions compared to the western zone. This increase can be attributed to the extensive cultivation of fodder crops for animal feeding in the eastern region. Consequently, these fields required higher fertilizer inputs, which contributed to the elevated emission levels. Similar findings were reported by Gollnow *et al.* (2014) [4] and Gerber *et al.* (2013) [3].

3.2.4 Emission from diesel use from eastern and western zones of Haryana

The total CO_2 equivalent emissions from diesel usage in the eastern and western zones of Haryana were 1736.08 and 1569.67, respectively, as presented in Table 2. Comparable values were observed between the two zones; however, diesel emissions were numerically higher in the eastern zone compared to the western zone. This difference can be attributed to greater fuel energy consumption in the eastern zone due to a variety of activities such as land preparation (harrowing and ploughing), transportation of feed and mineral mixtures from markets to support highly productive animals, and dung disposal. Consequently, these factors resulted in increased diesel emissions from the eastern zone. In contrast, the western zone recorded lower overall diesel emissions, partly due to limited land availability for fodder cultivation. Similar findings—indicating lower greenhouse gas emissions from smaller farms—were reported by Pirlo *et al.* (2013) [10], Gollnow *et al.* (2014) [4], and Thoma *et al.* (2013) [11].

3.2.5 Emission from dung (methane and nitrous oxide) from eastern and western zones of Haryana

The total CO_2-equivalent emissions from dung in the eastern and western zones of Haryana were 7.60 and 6.24, respectively, as shown in Table 2. Similar values for dung-related emissions were observed between the two zones. However, the eastern zone exhibited numerically higher dung emissions compared to the western zone. This can be attributed to the presence of larger farms in the eastern region, which have higher production levels and greater dry matter intake, ultimately resulting in increased dung output and emissions. Comparable findings were reported by Gerber *et al.* (2011) [3], Thoma *et al.* (2013) [11], and Pirlo *et al.* (2013) [10].

3.2.6 Total emissions from eastern and western zones of Haryana

The total CO_2 equivalent emissions from the eastern and western zones of Haryana were 129,623.17 and 113,826.42, respectively, as presented in Table 2. Comparable trends in total CO_2 equivalent emissions were observed between the two zones. However, the eastern zone recorded numerically higher emissions than the western zone. This higher Global Warming Potential (GWP) in the eastern zone can be attributed to greater emissions from all contributing sources—enteric fermentation, manure management, fertilizer usage, electricity consumption, and diesel usage—compared to those in the western zone.

3.3 GWP per Kg FPCM from eastern and western zones of Haryana

The Global Warming Potential (GWP) per kilogram of Fat and Protein Corrected Milk (Kg FPCM) through various sources enteric fermentation, dung, fertilizer, electricity, and diesel in the eastern and western zones of Haryana is presented in Table 3.

The CO_2 equivalent per Kg FPCM from enteric emissions was 0.939 in the eastern zone and 0.930 in the western zone. From fertilizer inputs, the CO_2 equivalent was 0.271 and 0.253 for the eastern and western zones, respectively. The CO_2 equivalent from electricity use per Kg FPCM was 0.199 in the eastern zone and 0.192 in the western zone. Diesel-related emissions were 0.020 and 0.021 CO_2 equivalent/Kg FPCM for the eastern and western zones, respectively. Emissions from dung contributed 0.000079 and 0.000076 CO_2 equivalent/Kg FPCM in the eastern and western zones, respectively.

Statistically, there were no significant differences ($p<0.05$) in GWP per Kg FPCM across the eastern and western zones for any of the sources mentioned enteric, dung, fertilizer, electricity, or diesel. However, numerically, the eastern zone consistently showed slightly higher GWP values than the western zone.

The total GWP per Kg FPCM for the eastern and western zones was 1.43 and 1.40, respectively, as shown in Table 3 and Figure 1. Although the difference was not statistically significant, the eastern zone recorded a marginally higher total GWP per Kg FPCM. This increase can be attributed to higher energy consumption for general farm operations, elevated electricity usage, greater fertilizer application, and higher dry matter intake (DMI) by dairy animals.

Similar observations were reported by Thoma *et al.* (2013) [11] and Pirlo *et al.* (2014) [9]. Paul (2018) [8], in her study conducted during 2016-17 on organized dairy farms in both zones, reported carbon footprints (CF) of 1.15 Kg CO_2 eq/FPCM in the eastern zone and 1.26 Kg CO_2 eq/FPCM in the western zone.

The carbon footprint encompasses all greenhouse gas emissions from milk production, including methane from enteric fermentation, methane and nitrous oxide from manure management, and carbon dioxide from the use of electricity and diesel within the defined boundaries of the study.

The slight regional variation in CF values indicates differences in comprehensive farm management practices. These include feeding strategies, manure handling methods, and the efficiency of energy use such as diesel, electricity, kerosene, urea, or lime application. Among all sources, biogenic methane emissions posed the greatest challenge. Enteric methane production is influenced by several factors, including herd size, productivity, feeding patterns, forage quality, and concentrate intake.

The region is known for growing crops like wheat and paddy (forming part of the wheat belt), and farmers extensively use wheat and paddy straw as dry fodder. However, the digestibility of these straws is relatively low, leading to poor feed energy conversion efficiency in dairy animals.

Table 1: MY (kg), FPCM (kg) and LU based on different zones of Haryana

Parameters	Eastern Zone	Western Zone	SEM	P-value
MY (kg)	103948.84	92928.39	9049.61	NS
FPCM (kg)	99992.54	85961.62	8487.05	NS
LU	404.11	379.18	21.99	NS
MY/LU	249.36	242.54	15.84	NS
FPCM/LU	239.12	223.15	14.19	NS

Table 2: GWP (kg) based on different zones of Haryana

Parameters (kg)	Eastern Zone	Western Zone	SEM	P-value
Enteric	85683.46	75753.54	5859.01	NS
Fertilizer	22523.72	19653.81	1224.96	NS
Electricity	19672.31	16843.15	1640.47	NS
Diesel	1736.08	1569.67	93.48	NS
Dung	7.60	6.26	0.58	NS
GWP	129623.17	113826.42	8641.97	NS

Table 3: GWP (kg per kg FPCM) based on different zones of Haryana

Parameters (kg per kg FPCM)	Eastern Zone	Western Zone	SEM	P-value
Enteric	0.939	0.930	0.031	NS
Fertilizer	0.271	0.253	0.016	NS
Electricity	0.199	0.192	0.004	NS
Diesel	0.020	0.021	0.001	NS
Dung	0.0000791	0.0000756	0.0000022	NS
GWP	1.43	1.40	0.05	NS

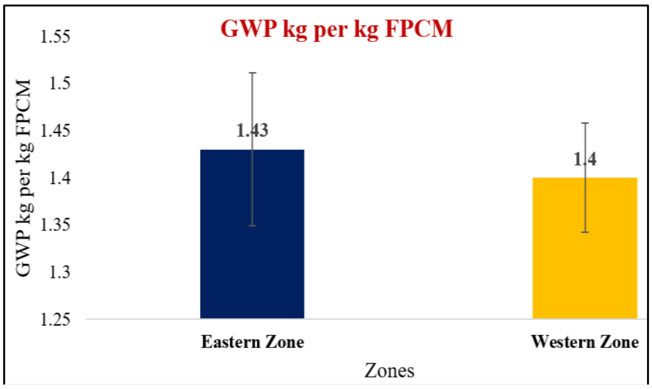

Fig 1: GWP (kg per kg FPCM) based on different zones of Haryana

4. Conclusions

The study found no significant differences ($p>0.05$) in the global warming potential (GWP) per kilogram of fat and protein corrected milk (FPCM) between the eastern and western zones of Haryana across all emission sources, including enteric fermentation, dung management, fertilizer use, electricity, and diesel consumption. The total GWP per kg of FPCM was 1.43 kg CO_2-eq in the eastern zone and 1.40 kg CO_2-eq in the western zone, indicating comparable carbon footprints across regions. These results suggest that regional variations within Haryana have minimal impact on the overall GWP of milk production, highlighting the need for targeted mitigation strategies focusing on primary emission sources rather than geographic location.

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