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Research Article

The Carbon Footprint of Cattle Beef in Rural Areas in Southwestern Vietnam

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Abstract | A study was conducted to investigate beef production's carbon footprint in rural areas in southwestern Vietnam, covering the upstream of calf production, feeds, and cattle feeding to the downstream of slaughter, producing fresh beef sold at local markets. The "Cradle-to-Gate" process of the Life Cycle Assessment approach was utilized for analysis, in conjunction with Tier 2 algorithms from the Intergovernmental Panel on Climate Change, and factors relating to feeding practices were altered based on survey results and existing studies under comparable conditions. The survey, conducted in early 2025, used questionnaires to collect data from 120 beef cattle households in southwestern Vietnam, involving 223 individual cattle. Results showed that emission factors from the upstream to the cattle production stage were on average ± standard error of 28.9 ± 0.928 (8.19-59.1) kg of carbon dioxide equivalent (CO_2e) per kilogram of live weight sold. After slaughter, emission factors were, on average, 59.5 ± 1.89 (17.4-121) and 68.8 ± 2.18 (20.2-140) kg CO_2e per kilogram of CW and FBW, respectively. The contribution sources were upstream (calves, feed production, and other supplies), which accounted for 35.8%; on-farm stage (animal care, enteric fermentation, manure management, and other supplies), which accounted for 63.7%; and the downstream (slaughter, waste management, and other supplies) stage, which accounted for 0.529%. The carbon emission cost for earning 1 million VND by households was 813 ± 42.3 kg CO_2e after cattle production and 608 ± 24.9 kg CO_2e on the post-slaughter stage. Feeding scenarios involving high concentrate levels up to 20-40% dry matter (DM) in the diet, which meet cattle nutritional requirements, showed significant potential to mitigate CO_2e emissions by 50-56% during the on-farm production stages and 28–30% CO_2e per kilogram of beef for the entire system. Further research is necessary to validate the hypotheses in these scenarios and to develop emission factors that better reflect the conditions in southwestern Vietnam.

Keywords | Carbon emission, Greenhouse gas, Beef production, Household livestock systems, Mitigation strategies, Life cycle assessment

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INTRODUCTION

Addressing greenhouse gas (GHG) emissions has become a major focus in the context of climate change, economic advancement, and food security. Vietnam, through its commitment at COP26, has pledged to reach net-zero emissions by 2050. One of the nation's greatest challenges lies in reducing 46.95 million tons of CO_2e from the livestock sector by 2030, with digestion processes alone accounting for 67.0% of these emissions (MONRE, 2022). Numerous international studies have established that cattle production generates more GHG than other livestock species, largely due to enteric fermentation, especially in developing nations (Gerber *et al*., 2013). While substantial research has focused on the carbon footprint (CF) of livestock globally, localized studies, particularly in rural regions of developing countries like Vietnam, are still limited. According to the IPCC (2019), CF assessments are essential for identifying key emission sources, proposing mitigation strategies, and reducing environmental harm. The most common method for investigating CF in livestock systems is the Life Cycle Assessment (LCA), supported by algorithmic frameworks developed by the IPCC (2006, 2019). Through "Cradle-to-Gate" LCA, the beef production chain is evaluated from calf production and feed to respiration, enteric fermentation, manure handling, energy use, sanitation, and transportation, with enteric fermentation typically being the largest contributor (Desjardins *et al*., 2012). Emissions from enteric fermentation and manure management are calculated using three tiers defined by the IPCC. Tier 1 uses default values, Tier 2 incorporates feed intake levels, and Tier 3 employs country-specific methodologies. While Tier 3 is used in some developed countries, Tier 2 remains the most widely implemented globally and is standard in Vietnam (MONRE, 2022). Under Tier 2, methane emissions from enteric fermentation are based on gross energy intake (GEI) and a default methane conversion factor (Ym) of 6.5%. However, Kaewpila and Sommart (2016) found that Zebu cattle (*Bos indicus*) on low-quality tropical diets exhibited higher Ym values, up to 8.2%. Similarly, Hiep *et al*. (2016) reported that crossbred Sindhi cattle in Vietnam had a Ym value of 8.48%.

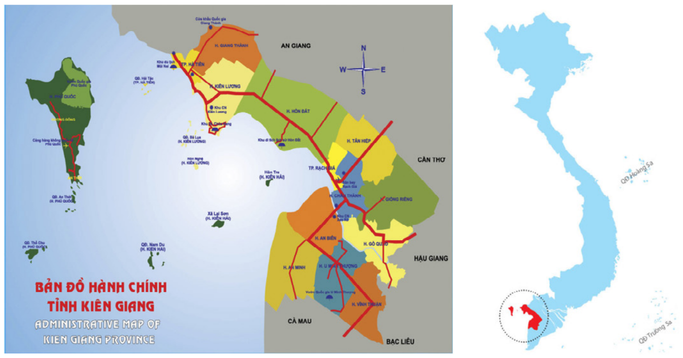
Southwestern Vietnam stands out for its distinctive geography, climate, and culture, being part of the Mekong Delta with waterlogged, nutrient-rich soils. The region is a vital agricultural hub. Local consumers tend to prefer fresh, locally sourced meat over processed or preserved products, primarily due to perceived taste and health benefits (Hung *et al*., 2022; Markoni *et al*., 2023). Most cattle raised in the region are Sindhi crossbreeds (*Bos indicus*), which account for 90.2% of the total herd. Southwestern Vietnam made up about 14.1% of the national cattle population, with an increase at an average annual rate of around 1.34% since 1995 (GSO, 2024). Production in this area is largely unmechanized and based on smallholder models, making precise CF estimation challenging. Traditional feeding relies on rice straw, wild grasses, and other agricultural by products, with manure typically left to dry naturally (Thu and Dong, 2023). As such, applying default IPCC parameters without region-specific adjustments may not yield accurate CF estimates. The present study aims to investigate the CF of beef cattle production from households in rural Southwestern Vietnam, offering data for future emission mitigation strategies and enhancing scientific knowledge of CF in low-input, smallholder livestock systems.

MATERIALS AND METHODS

No experimental interventions or animal handling were conducted; data were obtained retrospectively and via non-invasive on-farm observations. Farms operated in compliance with Vietnam's Law on Livestock Husbandry (No. 32/2018/QH14). Per institutional policy, this non-interventional, retrospective survey was exempt from animal ethics review.

Study site and survey design

The study was conducted in early 2025 across five rural districts of the former Kien Giang province in southwestern Vietnam (9°23'50-10°32'30 N; 104°26'40-105°32'40 E, Figure 1), representing typical lowland beef cattle farming systems. Data were collected through structured questionnaires administered to 120 randomly selected cattle-raising households, encompassing 223 individual cattle. The survey gathered information on animal characteristics (e.g., age, weight, breed, sex), housing, manure management, feeding practices, pasture availability, feed composition, and production costs and revenues. The surveyed locations were characterized by a tropical monsoon climate with hot and humid conditions, temperatures ranging from 17-37°C, annual rainfall between 1,800-2,300 mm, and humidity levels of 78-85%. The rainy season spans from April to November, and the dry season spans from December to March, with December being the coldest month (Ha, 2023).



(A) (B)

Figure 1: The surveyed site: (A) Selected districts: Giang Thanh (dark orange, northern border with Cambodia); Kien Luong (yellow, western coastal area); Hon Dat (green, coastal district adjacent to the Gulf of Thailand); Chau Thanh (blue, coastal zone near Rach Gia); and Vinh Thuan (dark orange, southernmost inland district); (B) General administrative map of the former Kien Giang province (Source: PCKGP, 2020).

Life cycle system boundary

The LCA approach (Opio *et al*., 2013) was used in this study to analyze the CF of beef cattle, as illustrated in Figure 2. The "Cradle-to-Gate" process in LCA was applied, encompassing three main stages: Upstream, core (on-farm production), and downstream. The upstream stage includes calf production, feed production, transportation, and other supplies; the core stage involves animal care, environmental control, enteric fermentation, manure management, transportation, and other supplies; and the downstream stage includes slaughtering, waste management, meat processing/preservation, transportation, and other supplies. "Field-based" denotes on-farm primary activity data (intake, management, and purchase/sale records) combined with IPCC Tier-2 modeling; when Vietnam-specific emission factors were unavailable, system-matched proxies were used.

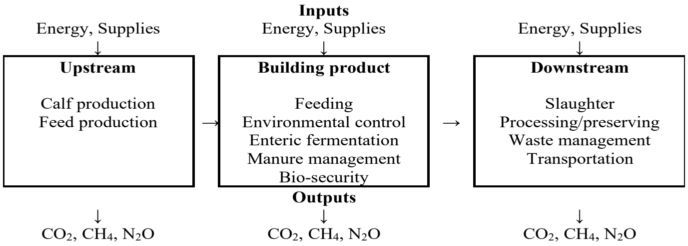


Figure 2: Life cycle system boundary of the beef cattle.

Functional units

Carbon footprint was expressed per kilogram of live weight (LW), carcass weight (CW), and fresh beef weight (FBW), as well as per animal and million VND of income. "Income" was defined as gross cash revenue from cattle sales (not net profit); family labor and land opportunity costs were not monetized. Feed conversion ratio (FCR), weight gain (WG), body length and heart girth, dry matter intake (DMI), dietary forage, and concentrate proportion, feeding days, and other retrospective data were used to calculate emission intensities. The data from the field survey are summarized in Table 1.

Table 1: Descriptive data (n=223) from the field survey for the study.

Variables	Minimum	Maximum	Mean	SE
Feeding duration, days	60	3285	1140	53.9
Initial weight, kg	25	350	116	5.07
Final weight, kg	50	650	357	10.4
Dry matter intake, kg/day	0.457	7.76	4.26	0.116
Concentrate proportion, % DM	0	7.83	0.846	0.099
Weight gain, kg/day	0.056	0.972	0.277	0.011
Feed conversion ratio	2.07	87.5	22.0	1.18
Gross energy, MJ/kg DM	16.0	16.4	16.2	0.059
Digestible energy, MJ/kg DM	9.62	9.82	9.73	0.053
Metabolizable energy, MJ/kg DM	7.83	8.04	7.95	0.054
Crude protein, % DM	5.86	7.67	6.81	0.033

DM = dry matter; MJ = megajoule; SE = standard error.

Measurement and calculation

Live weight of feeding cattle was calculated using the Shaeffer model (Wanderstock and Salisbury, 1946), or by weighing or interviewing for newly acquired calves and sold cattle:

$$LW = HG^2 \times BL/300$$

Where: LW is in pounds, HG and BL are in inches, and HG and BL measurements follow the guidelines of Rashid *et al.* (2015). The Shaeffer equation was used because smallholder farms in the study do not have livestock (large-animal) weighing scales; the method remains field-feasible, low-cost, and standardized in Vietnam (TCVN 5286: 1990).

Weight gain (WG) was determined from the period between cattle acquisition and survey time. Feed intake was determined over 3 days by daily weighing of provided feed and subtracting refuse for the next day to determine DMI (kg) and the proportion of concentrate (C) in the diet, or DMI is estimated according to Azevêdo *et al.* (2016) for Zebu cattle when DMI cannot be measured directly:

$$DMI = -1.303 + 0.0029 \times C - 0.00005 \times C^2 + 0.0843 \times LW^{0.75} + 2.243 \times WG - 0.271 \times WG^2$$

These intake data were collected on-farm using calibrated scales (not self-reported from retrospective information of the farmer); for newly purchased animals or grazing where early-period weighing was infeasible, DMI was estimated (Azevêdo *et al.*, 2016) and period-weighted with the field-measured DMI at the survey.

Gross energy (GE), crude protein (CP), and Ash content in the diet were based on the ratio of feedstuffs in the diet and using data: GE for grass 17, rice straw 16, concentrate 19 MJ/kgDM; CP for grass 11, rice straw 5.7, concentrate 12% DM; and Ash for grass 10, rice straw 13.5, concentrate 10% DM referenced from NIAH (2001). Digestible energy (DE) was determined according to IPCC (2006, 2019) as 0.6 of GE. Metabolizable energy (ME) was calculated according to Weiss and Tebbe (2019).

$$ME = 1.01 \times DE - 0.45$$

Where; DE and ME are in Mcal/kg of DM (to convert to MJ, multiply by 4.1867).

The carcass components after slaughter used data from studies by Linh *et al.* (2021), Mo (2018a), and Hue *et al.* (2009), with carcass at 48.92% of LW and lean meat at 42.34% of LW. Other input variables were determined through interviews and observations, including: number of days of feeding, labor, energy (electricity, gas, firewood), water, transportation, biosecurity, waste management systems, and irregular feed types.

Respiratory emissions were calculated according to Madsen *et al.* (2010) and Kjeldsen *et al.* (2024):

$$CO_2\ (l/d) = HP\ (kJ/d)/21.75$$

Where: 21.75 = conversion factor of 1 kJ HP to l CO_2, kg CO_2 = l CO_2 × 1.757/1000 (32°C, 101.317 Pa). The HP (heat production) of the animal was calculated based on LW (kg), WG (kg/day), and GE (MJ/kgDM) according to CIGR (2002):

$$HP\ (W/d) = 7.64 \times LW^{0.69} + WG \times [(23/GE - 1)] \times [(57.27 + 0.302 \times LW)/(1 - 0.171 \times WG)];\ kJ/d = (1\ W/d \times 60\ seconds \times 60\ minutes \times 24\ hours)/1000$$

Enteric methane emissions (CH_4e, kg) determined according to IPCC (2006, 2019):

$$CH_4e = DMI \times Ym/100 \times GE/55.65$$

Where: Ym = 37.7 + 19.71 × DE/ME – 50.7 × ME/DE (Kaewpila and Sommart, 2016), and 55.65 = methane energy content.

Methane from manure (CH_4f, kg) according to IPCC (2006, 2019):

$$CH_4f = \{[GE \times DMI \times (1 - 0.6) + 0.04 \times GE \times DMI] \times (1\text{-}Ash)/GE\} \times 0.1 \times 0.67 \times 0.02$$

Where: 0.6 = digestion rate, 0.04 = urine energy, 0.67 = conversion factor from m^3 CH_4 to kg, 0.1 = maximum CH_4 generation potential of manure, 0.02 = methane conversion factor for dry manure management systems.

Nitrous oxide emissions (N_2Of, kg) from manure according to IPCC (2006, 2019):

$$N_2Of = N_2Odf + N_2Ovf + N_2Olf$$

Where: N_2Odf = Nex × 0.02 × 44/28, due to direct emissions; N_2Ovf = Nex × 0.2 × 0.01 × 44/28, emissions due to volatilization; N_2Olf = Nex × 0.3 × 0.0075 × 44/28, emissions due to leaching; Nex = (1-0.07) × DMI × CP/6.25, nitrogen excreted in manure; 0.02 = N_2O emission conversion factor for dry manure management systems; 44/28 = conversion from N_2O-N to N_2O; 0.2 = fraction of nitrogen that volatilizes as NH_3 and NOx in dry manure management systems; 0.01 = emission factor for N_2O from atmospheric nitrogen; 0.3 = fraction of nitrogen lost due to leaching; 0.0075 = emission factor for N_2O from leached nitrogen; 0.07 = fraction of maintenance nitrogen; 6.25 = conversion of nitrogen from protein.

Emissions from solid waste (CH_4ssw and N_2Ossw, kg) from slaughterhouses are estimated similarly to manure (Ngwabie *et al.*, 2019), but the VS of solid waste and nitrogen of slaughterhouse solid waste are determined differently:

$$CH_4ssw = 0.1 \times 0.67 \times 0.02 \times 0.275 \times 0.189 \times LW;\ N_2Ossw = N_2Odsw + N_2Ovsw + N_2Olsw$$

Where: N_2Odsw = 0.031428571 × Nsw, direct emissions; N_2Ovsw = 0.003142857 × Nsw, emissions due to volatilization; N_2Olsw = 0.003535714 × Nsw, emissions due to leaching; Nsw = 0.275 × 0.01865 × LW, nitrogen excreted from slaughterhouse solid waste; 0.1 = maximum CH_4 generation potential of manure; 0.67 = conversion factor from m^3 CH_4 to kg; 0.02 = methane conversion factor for dry manure management systems; 0.275 = ratio of waste to cattle body weight (Jayathilakan *et al.*, 2012); 0.189= volatile content of waste (Musa et al., 2020); 0.01865= nitrogen content of waste (IPCC (2006, 2019)).

Emissions from wastewater (CH_4ww and N_2Oww, kg) from slaughterhouses were estimated according to IPCC (2006, 2019):

$$CH_4ww = 13.9 \times 0.25 \times 0.1 \times Vww = 0.3475 \times Vww;\ N_2Oww = 0.212 \times 1.1 \times 1.25 \times 0.005 \times 44/28 \times Vww = 0.002290357 \times Vww$$

Where: 13.9 = COD of wastewater, kg/m^3 (Budiyono *et al.*, 2011); 0.25 = maximum CH_4 generation potential; 0.1 = methane correction factor; 0.005 = N_2O emission factor for wastewater; 44/28 = conversion from kg N_2O-N to N_2O; 0.212 = nitrogen content of wastewater, kg/m^3 (Budiyono *et al.*, 2011); 1.1 = factor for additional nitrogen in wastewater; 1.25 = factor for co-discharged nitrogen into wastewater systems; Vww = volume of wastewater, m^3, determined as 90% of water consumption (Shende *et al.*, 2022). Other indirect emissions were calculated based on emission factors in Table 2.

Table 2: Emission factor of other sources.

Variables	Value	Unit	Sources
Calf production	30.7	Kg CO_2e/kgLW	Basarab *et al.* (2012)
Rice straw	0.072	Kg CO_2e/kg	Deka *et al.* (2025)
Grass	0.018	Kg CO_2e/kg	Somjai and Suwan (2020)
Concentrate	0.27	Kg CO_2e/kgDM	Flachowsky (2011)
Electricity	0.6592	Kg CO_2e/kWh	DCCV (2024)
Workforce	0.009	Kg CO_2e/h	Walsh *et al.* (2008)
Gasoline	2.301	Kg CO_2e/l	IPCC (2006, 2019)
Diesel	2.739	Kg CO_2e/l	IPCC (2006, 2019)
Wood	1361	Kg CO_2e/m^3	IPCC (2006, 2019)

To examine the impact on global warming potential through assessment over 100 years (IPCC, 2007), GHG types were converted to carbon dioxide equivalent units (CO_2e), using 25 for CH_4 and 298 for N_2O.

The development of feeding scenarios to mitigate emissions was based on husbandry practices, locally available feed conditions, and nutritional requirements of Zebu cattle, with the hypothesis of increasing the proportion of concentrate to meet nutritional requirements, then predicting DMI according to Mo (2018b) and WG according to Azevêdo *et al.* (2016). Nutritional requirements were then determined using the tool by Benedeti *et al.* (2016), with input variables of initial and final LW from the survey and WG according to prediction results.

Data analysis

Descriptive statistical analysis was conducted by using Minitab 21 (2022) software to calculate the minimum and maximum values, mean, and standard error (SE) for all variables.

RESULTS AND DISCUSSIONS

Carbon footprint of beef

The results of the calculation and analysis of the CF of beef in rural areas in Southwestern Vietnam are presented in Tables 3, 4 and Figures 3, 4.

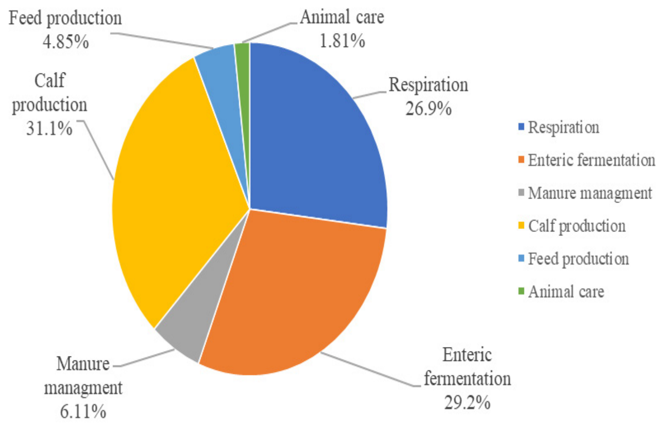


Figure 3: Sources of carbon emissions at the farm-gate.

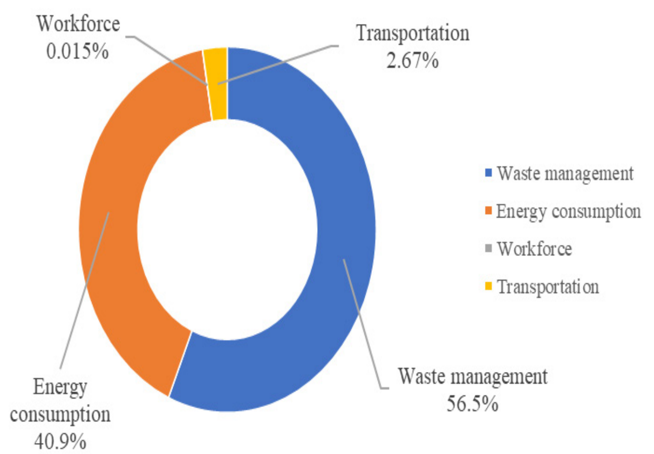


Figure 4: Sources of carbon emissions at the slaughterhouse.

Table 3: Carbon footprint of beef cattle fed by households at the farm-gate

Items	Min.	Max.	Mean	SE
Calf production, kg CO_2e/head	768	10745	3572	156
Feed production, kg CO_2e/head	5.05	1951	557	29.9
Respiration, kg CO_2e/head	44.5	11063	3081	169
Enteric fermentation, kg CO_2e/head	30.7	12560	3354	187
Manure management, kg CO_2e/head	5.96	2438	700	37.6
Animal care, kg CO_2e/head	8.74	1617	208	15.9
Total, kg CO_2e/head	866	35478	11472	537
CO_2e/head/day, kg	3.65	48.4	10.0	0.285
CO_2e/head/year, kg	1333	17673	3640	104
CO_2e/kg of WG, kg	9.36	237	48.9	2.33
CO_2e/kg of LW, kg	8.19	59.1	28.9	0.928
CO_2e/million VND of income, kg	111	5173	813	42.3

CO_2e = equivalent carbon dioxide; WG = weight gain; LW = live weight; SE = standard error;1 USD = 25,605 VND. Animal care included a workforce of feeding, environmental control, and biosecurity. Calf and feed production included transportation.

The assessment (Table 3) revealed that the average total GHG emissions per animal were 11,472 ± 537 kg CO_2e/head, with values ranging from 866 to 35,478 kg CO_2e/head. This corresponds to an estimated 10.0 ± 0.285 kg CO_2e/head/day, or 3,640 ± 104 kg CO_2e/head/year. Emission intensity per unit of WG was calculated at 48.9 ± 2.33 kg CO_2e/kg, while emissions per kilogram of LW reached 28.9 ± 0.928 kg CO_2e/kg. These values are substantially higher than those typically reported in developed countries. For instance, Desjardins *et al.* (2012) documented emission levels between 7.9 and 22.4 kg CO_2e/kg LW, with averages of 14.8 kg CO_2e/kg in the U.S. and 19.2 kg CO_2e/kg in pasture-based systems. Emissions in France ranged from 14.3 to 18.3 kg CO_2e/kg LW, while in Sweden, they were around 11.6 kg CO_2e/kg, and in Canada and Australia, values ranged from 8.4 to 15.3 kg and 7.9 to 12.7 kg CO_2e/kg LW, respectively. Even Brazil, with its extensive production systems, reported lower average intensities of 14.3–22.4 kg CO_2e/kg LW (Dick *et al.*, 2015). The elevated emission intensities observed in this study are likely due to traditional low-nutrition feeding systems and the use of low-performing indigenous cattle breeds, which contribute to longer fattening periods. These findings align with the conclusions of Dick *et al.* (2015), van Lingen *et al.* (2018), and Florindo *et al.* (2017), all of whom emphasized that genetic improvement, enhanced feeding strategies, and reduced fattening time are effective in lowering emission intensity per unit of product.

The higher CF in this study is explained by three linked features of the Mekong Delta smallholder system: low-quality roughages (rice straw and native grasses) with crude protein typically around 5–7% DM; predominance of *Bos* *indicus* with lower feed efficiency than specialized beef breeds; and prolonged fattening (mean feeding duration ≈1,140 days in our survey), which raises lifetime emissions per animal. The large shares from respiration (26.9%) and enteric fermentation (29.2%) are consistent with these constraints and point to the need to improve diet quality and shorten cycles.

The results in Table 4 show that the CF across the full rural beef production system in southwestern Vietnam also varies widely. Total emissions ranged from 926 to 35,571 kg CO_2e/head, with a mean value of 11,548 kg CO_2e/head (SE = 537), which is comparable to findings by Florindo *et al.* (2017) in Brazil, where production intensity and feed composition varied significantly. When emissions were expressed per CW, the average CF was 59.5 kg CO_2e/kg, ranging from 17.4 to 121 kg CO_2e/kg. For edible beef, the CF rose further to 68.8 kg CO_2e/kg, well above global averages. For comparison, Desjardins *et al.* (2012) reported 8.0–19.2 kg CO_2e/kg LW for systems in the U.S. and Australia, while Dick *et al.* (2015) recorded 18.3 kg CO_2e/kg in improved systems and 45.1 kg CO_2e/kg in extensive systems in Brazil.

Table 4: Carbon footprint of beef in the entire production system.

Stage	Min.	Max.	Mean	SE
Upstream, kg CO_2e/head	774	11599	4144	174
On-farm production, kg CO_2e/head	91.8	27678	7343	399
Downstream, kg CO_2e/head	22.8	96.0	61.0	1.20
Total, kg CO_2e/head	926	35571	11548	537
CO_2e/kg of CW, kg	17.4	121	59.5	1.89
CO_2e/kg of FBW, kg	20.2	140	68.8	2.18
CO_2e/million VND of income, kg	106	2010	608	24.9

CO_2e: equivalent carbon dioxide; CW = carcass weight; FBW = fresh beef weight; SE = standard error;1 USD = 25,605 VND.

Within the production stages, the on-farm production phase was the largest source of emissions, with an average of 7,343 kg CO_2e/head, consistent with studies by Gao *et al.* (2014) and Ramírez-Restrepo *et al.* (2023). Upstream emissions related to feed and calf inputs averaged 4,144 kg CO_2e/head, while the downstream stage contributed minimally, at 61 kg CO_2e/head. The carbon cost per unit of income was calculated at 608 kg CO_2e per million VND, indicating low carbon-economic efficiency, as similarly noted by Murphy *et al.* (2017). The high CF values observed in this region emphasize the need for interventions such as improved cattle genetics, more efficient feed use, shorter production cycles, and enteric methane mitigation strategies (Samsonstuen *et al.*, 2019). Integrated ecological farming models have also demonstrated potential in lowering emissions, as shown in the work of Guo *et al.* (2022).

The breakdown of emission sources across the beef production system is illustrated in Figure 3. Among the various contributors, enteric fermentation emerged as the dominant source, averaging 3,354 ± 187 kg CO_2e/head, which accounted for 29.2% of total emissions. This was followed closely by respiratory emissions, contributing 3,081 ± 169 kg CO_2e/head or 26.9%. Emissions associated with calf production were also substantial, reaching 3,572 ± 156 kg CO_2e/head, equivalent to 31.1% of the total. Other sources contributed smaller proportions. Manure management emitted 700 ± 37.6 kg CO_2e/head (6.1%), while emissions from feed production and animal care were 557 ± 29.9 kg CO_2e/head (4.85%) and 208 ± 15.9 kg CO_2e/head (1.81%), respectively. Altogether, the three main sources, enteric fermentation, respiration, and calf production, accounted for approximately 87% of total emissions. These findings underscore the crucial role of animal physiology and biological processes in GHG emissions, particularly methane production from enteric digestion and energy use for maintenance. This result aligns with van Lingen et al. (2018), who emphasized the dominant contribution of digestion and excretion in total livestock emissions. It is also consistent with the broader literature indicating that enteric methane is the single largest emission source in ruminant livestock systems (Desjardins *et al.*, 2012; Ramírez *et al.*, 2023).

In the downstream stage of the system, shown in Figure 4, the largest contributor to emissions was waste management, accounting for 56.5% of emissions during slaughter and post-slaughter handling. Energy consumption followed, representing 40.9% of downstream emissions, which primarily originated from lighting, water pumping, and refrigeration at small-scale slaughter facilities. The remaining contributions came from transportation (2.67%) and labor (0.015%), the latter being negligible due to the manual and low-mechanization nature of most rural slaughterhouses. Although downstream emissions constituted a small fraction of total system emissions, just 0.53%, they are not insignificant in the context of local environmental management. The small downstream share reflects informal, low-energy slaughter, characterized by manual processing, rapid sale of fresh meat, and limited or absent refrigeration. Waste handling is rudimentary, with by-products often reused locally. While this explains the low current footprint, downstream emissions could rise if the cold chain is expanded. Improper waste disposal and inefficient energy use may pose additional sustainability risks. Improvements such as adopting biogas technology for waste treatment and using energy-efficient equipment in slaughter operations could reduce these emissions further.

Overall, the results highlight that while upstream and production-phase interventions are most effective for reducing total emissions, downstream improvements offer complementary benefits and should not be overlooked in mitigation planning.

Dietary scenarios for emission mitigation

The study modelled three dietary adjustment scenarios to evaluate their effectiveness in reducing carbon emissions compared to current feeding practices, as shown in Tables 5 and 6. These scenarios were designed by modifying DMI proportions of rice bran, soybean meal, grass, and rice straw to improve the nutritional profile and energy balance of cattle diets. Scenario 1 (≈95% grass) is used as a benchmark to show the upper bound of mitigation with high-forage diets. Given the limited grassland in the Mekong Delta, more feasible options are silage making and improved forages within crop–livestock integration. Scenarios 2 and 3, therefore, better represent practical pathways.

Table 5: Cattle performance in dietary scenarios for emissions mitigation.

Items	Scenario diets		
	1	2	3
Rice bran, %DMI	20	40	12
Soy meal, %DMI	0	0	28
Grass, %DMI	80	43	20
Rice straw, %DMI	0	17	40
DMI, kg/day	4.63	4.75	4.75
ME content, MJ/kg DMI	9.35	9.37	9.37
CP content, % DMI	10.5	10.5	10.5
Feeding-day	502	467	467
Weight gain, kg/day	0.480	0.516	0.516
Feed conversion ratio	10.8	10.5	10.1

DMI = dry matter intake; ME = metabolizable energy; CP = crude protein; MJ = megajoules. Scenario diets 1: 5% rice bran + 95% grass; 2: 11.5% rice bran + 2.0% soy meal + 68.0% grass + 18.5% rice straw; and 3: 25.5% concentrate + 4.5% soy meal + 10.5% grass + 59.5% rice straw (as-fed basis, while percentages in Table 5 are on a DMI basis).

All three alternative diets led to notable improvements in animal performance. In Scenario 1, a diet of 95% grass and 5% rice bran increased DMI from 4.26 kg/day (field survey) to 4.63 kg/day. The ME content also improved, rising from 7.96 to 9.35 MJ/kg of DMI. The CP content increased from 6.90% to 10.5%, while the average daily WG rose significantly from 0.277 kg to between 0.480 and 0.516 kg across all scenarios. These enhancements were accompanied by major gains in FCR, improved from 22.0 under traditional feeding to values between 10.1 and 10.8 in the dietary scenarios, demonstrating a more than twofold increase in feed utilization efficiency. Carbon emission levels also decreased substantially under the new feeding regimes. Total emissions per head were reduced from 11,533 kg CO_2e in the field survey to between 7,720 and 8,183 kg CO_2e, a reduction of approximately 29–33%. Emissions from the on-farm production phase alone decreased by over 50%, from 7,343 to around 3,234–3,679 kg CO_2e. When expressed per kilogram of final product, the emission intensity for FBW declined from 68.7 kg CO_2e/kg to 48.2–49.6 kg CO_2e/kg, making the system more aligned with international benchmarks. These results support previous findings that improving feed quality and balancing diets can effectively reduce GHG emissions from beef production (Gao *et al*., 2014; Dick *et al*., 2015; Samsonstuen *et al*., 2020).

Table 6: Carbon footprint of beef in dietary scenarios for emissions mitigation.

Items	Scenario diets		
	1	2	3
Upstream, kg CO_2e/head	3910	3947	3929
On-farm production, kg CO_2e/head	3615	3679	3234
Downstream, kg CO_2e/head	61.0	61.0	61.0
Total, kg CO_2e/head	8082	8183	7720
CO_2e/kg LW, kg	21.1	21.4	20.1
CO_2e/kg of CW, kg	43.0	42.5	41.7
CO_2e/kg of FBW, kg	49.6	49.1	48.2
Income, million VND/head	15.6	12.3	11.3
Income per month, million VND/head	0.930	0.792	0.728
Emission/income, kg CO_2e/million VND	484	618	632

LW = live weight; CO_2e=equivalent carbon dioxide; CW = carcass weight; FBW = fresh beef weight. Scenario diets 1: 5% rice bran + 95% grass; 2: 11.5% rice bran + 2.0% soy meal + 68.0% grass + 18.5% rice straw; and 3: 25.5% concentrate + 4.5% soy meal + 10.5% grass + 59.5% rice straw (as-fed basis). USD = 25,605 VND.

Despite the environmental benefits, the economic trade-offs were evident. Average income per animal was reduced from 20.5 million VND (field survey) to between 11.3 and 15.6 million VND under the dietary scenarios, primarily due to the shorter feeding duration and changes in feed composition. However, monthly income improved, increasing from 0.541 to 0.728–0.930 million VND, reflecting better productivity within a shorter production cycle. Nevertheless, carbon intensity per unit of income did not improve across all scenarios. Only Scenario 1 achieved better carbon-economic efficiency, with 484 kg CO_2e per million VND, while Scenarios 2 and 3 exceeded 600 kg CO_2e per million VND.

Although Scenario 1 yielded the best environmental and economic efficiency, it may not be feasible in the region due to limited grassland availability. Given the region's abundance of agricultural by-products such as rice straw, Scenarios 2 and 3, which incorporate higher levels of concentrates and by-products, may be more practical for local production systems and warrant further validation. Because Scenarios 2 and 3 reduce net income per head by about one-third to nearly one-half, uptake will require support (feed/forage subsidies, concessional credit, extension on forage/silage, and access to carbon credit schemes). Such measures align with Vietnam's COP26 livestock target (46.95 Mt CO_2e by 2030) and can de-risk adoption for smallholders. If realized at scale, the 50–56% per-animal reductions from improved diets would contribute materially to national targets, but costs, risk aversion, and land limits for forages remain key barriers to address.

Overall, adjusting diets can significantly lower CF and improve production efficiency, but targeted policy support, such as feed subsidies or local roughage yield improvements, is necessary to ensure adoption by smallholder farmers. These findings have important implications for climate-smart agriculture policy, particularly in supporting dietary improvement strategies in smallholder contexts. A limitation of this study, however, is the reliance on emission factors adapted from varied regional literatures, which may not fully capture the variability in smallholder systems. Future work should focus on direct measurement and modeling under local conditions. Although the study adopted IPCC Tier 2 because Tier 3 is not yet available in Viet Nam, and parameters were also localized (e.g., Ym for *Bos indicus* on tropical diets), the absence of Tier 3 remains a source of uncertainty. The use of predictive DMI for some cases may propagate error due to the infeasibility of direct measurement (e.g., grazing, newly purchased animals).

CONCLUSION

The study assessed the carbon footprint of beef in rural southwestern Vietnam using IPCC Tier 2 algorithms, with adjustments based on field surveys and literature reports with similar conditions. Results showed, on average, 28.9 ± 0.928 kg CO_2e/kg of LW, 59.5 ± 1.89 kg CO_2e/kg of CW, and 68.8 ± 2.18 kg CO_2e/kg of FBW. The carbon emission cost for earning 1 million VND of households from cattle farming in rural areas was 813 ± 42.3 kg CO_2e at the farm-gate and 608 ± 24.9 kg CO_2e at the post-slaughter. Scenarios of feeding at high concentrate levels from 20 to 40% DM in the diet could satisfy the nutrient requirement of cattle and mitigate carbon emissions by 50-56% in the on-farm production stage and 28-30% for the entire system. Further research is required to validate the hypotheses in the scenarios and develop emission factors that better align with the conditions in southwestern Vietnam.

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NOVELTY STATEMENT

This study presents the first life cycle assessment of beef production in rural southwestern Vietnam using field-based data and IPCC Tier 2 algorithms. It quantifies carbon footprint across the full production chain and demonstrates that dietary adjustment scenarios have a high potential to mitigate emissions for the product unit. It advances prior diet-focused studies by combining field-measured intake with a Tier-2, cradle to gate LCA (from cattle acquisition to slaughter) and by making explicit links to farm economics.

AUTHOR CONTRIBUTION

The conception, design, survey, interpretation, data analysis, writing, and final manuscript approval were done by D. Mo. This manuscript was prepared by the author with assistance from AI-based tools only for grammar checking and linguistic refinement. All scientific content and interpretation were conducted by the author.

Generative AI and AI-assisted technology statement

AI-based tools were used solely for grammar checking and language refinement. No generative AI tools were employed for creating, analyzing, or interpreting scientific content.

Conflict of interest

The author has declare no conflict of interest.

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