

Research Paper

Carbon footprint of Creole goat milk production in Peru under crop-residue and Andean shrubland systems

Richard Ayala Roldan^a, Miguel Paredes-Chocce^b, Hugo Castillo Doloriert^c,
David Godoy-Padilla^{d,e}, Juancarlos Alejandro Cruz-Luis^e, José Antonio Haro-Reyes^{b,*}

^a Facultad de Ciencias Veterinarias y Biológicas, Universidad Científica del Sur, Antigua Panamericana Sur 19, Villa EL Salvador, 15067 Lima, Peru

^b Estación Experimental Agraria Donoso, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria, Carretera Chancay – Huaral Km 5.6, Huaral 15200, Lima, Peru

^c Facultad de Medicina Veterinaria, Universidad Nacional Mayor de San Marcos, Av. Circunvalación 2800, 15021 San Borja, Lima, Peru

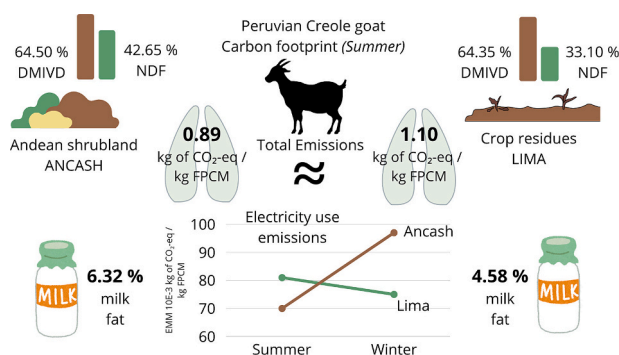
^d Grupo de Investigación en Mitigación y Adaptación de la Ganadería frente al Cambio Climático, Facultad de Zootecnia, Universidad Nacional Agraria La Molina, La Molina 15024, Lima, Peru

^e Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria, Av. La Molina 1981, La Molina 15024, Lima, Peru

HIGHLIGHTS

- Crop residues had higher protein but lower NDF than shrubland diets.
- Higher milk fat and total solids were observed in summer in Ancash system.
- Crop-residue (Lima) and shrubland (Ancash) systems showed similar total CFP.
- Fuel and electricity use emissions responded to system-season interactions

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paul Crosson

Keywords:

Climate change
Local breed
Methane
Caprine
Adaptation
Crop residue

ABSTRACT

CONTEXT: Goat farming in Peru is economically marginal yet essential for rural livelihoods and food security. Creole goats are managed extensively on native rangelands or crop residues, but their greenhouse gas emissions remain poorly quantified.

OBJECTIVE: To assess the carbon footprint (CFP) of Creole goat milk production under two contrasting extensive systems in Lima (crop-residue based) and Ancash (shrubland-based), Peru.

METHODS: A cradle-to-farm-gate life cycle assessment was conducted on six farms per system during winter and summer. Emissions of CH₄, N₂O and CO₂ were estimated using IPCC methodologies and expressed per kilogram of fat- and protein-corrected milk (FPCM). CFP were analyzed using univariate and mixed-effects models.

RESULTS AND CONCLUSIONS: System differences in farm characteristics were more pronounced during summer, when Ancash system, compared to Lima system, showed higher dietary fiber concentrations (42.65% vs 33.10%; $p < 0.001$) and produced milk with greater total solids content (15.38% vs 13.70%; $p < 0.05$). However, CFP did

* Corresponding author.

E-mail addresses: jaharoreyes@gmail.com, jharorey@purdue.edu (J.A. Haro-Reyes).

<https://doi.org/10.1016/j.agsy.2026.104993>

Received 31 December 2025; Received in revised form 27 July 2026; Accepted 20 September 2026

Available online 24 September 2026

0308-521X/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

not differ significantly between systems, ranging from 0.681 to 1.672 kg CO₂-eq kg⁻¹ FPCM, with enteric fermentation accounting for 74–79% of total emissions. Significant system × season interactions for fuel and electricity emissions revealed contrasting seasonal resource-use responses between systems. These findings indicate that seasonal dynamics are a major driver of emission variability, while overall CFP remained comparable between systems.

SIGNIFICANCE: This study provides the first CFP assessment of Creole goat milk production in Peru and highlights the importance of considering ecosystem and seasonal variability when assessing emissions from marginal goat systems.

1. Introduction

Goat production in Peru, as in many regions worldwide, remains marginal relative to other livestock species (Kerven, 2024; SIEA-MINAGRI, 2025). Nevertheless, it plays a critical role in rural livelihoods, providing income diversification and a reliable source of high-quality animal protein that contributes to local food security (Kerven, 2024). Production objectives vary across the country, with systems oriented toward either milk or meat depending on regional traditions, agroecological conditions, and market demand (Palomino Guerrero et al., 2024; Paredes Chocce et al., 2024; Sessarego et al., 2025).

Most goat farming in Peru is conducted under extensive systems, with only a limited number of intensive operations, largely private enterprises relying on dairy goat pure breeds such as Saanen (López Huamaní, 2021). Extensive systems are characterized by low capital inputs and a strong dependence on natural feed resources. Seasonal fluctuations in pasture availability lead to alternating periods of forage abundance and scarcity, prompting adaptive strategies such as transhumance to access ecosystems that remain productive when others decline (Sañudo, 2009). In addition, and often complementarily, many producers graze goats on cropland residues as an accessible, low-cost feed resource, contributing to residue management, field cleaning, weed control and nutrient recycling (Cottle and Cowie, 2016; Nahed Toral et al., 2021; Nampanzira et al., 2015). Beyond their feeding role, well-managed goat systems can deliver broader ecosystem services, including reduction of vegetation biomass and associated fire risk, support of biodiversity, and soil enrichment through manure deposition (Dubeuf et al., 2023; Modi et al., 2024).

Despite these benefits, goat production, like other anthropogenic activities, generates environmental impacts that remain poorly quantified. Globally, animal protein production accounts for approximately 6.2 Gt CO₂-eq, representing about 12% of total anthropogenic emissions estimated at 50 to 52 Gt CO₂-eq in 2015 (FAO, 2022). Within the livestock sector, small ruminants contribute around 7% of total greenhouse gas (GHG) emissions. Direct livestock emissions, mainly methane from enteric fermentation and methane and nitrous oxide from manure management, amount to 3.7 Gt CO₂-eq globally, corresponding to approximately 60% of total livestock emissions (FAO, 2023).

Enteric methane emissions thus represent a major environmental hotspot in goat systems, but also a key mitigation opportunity within the livestock sector. This is particularly relevant for Peru, which has committed to reducing national GHG emissions by 30% by 2030 (United Nations, 1992; Zucali et al., 2020). Previous studies in Peru have quantified the carbon footprint (CFP) of other livestock systems and proposed mitigation strategies, primarily based on grazing intensification to optimize emissions per unit of product, and on carbon sequestration through silvopastoral systems, enabling direct system-level reductions (Bartl et al., 2011; Ruiz-Llontop et al., 2025). However, the CFP of goat production systems has not yet been evaluated.

This knowledge gap extends to the diversity of production systems in which goats are raised. The regions of Lima and Ancash together account for nearly 19% of Peru's goat population, representing approximately 1.75 million head in 2024 (SIEA-MINAGRI, 2025). Beyond herd size, these regions exemplify contrasting feeding systems: in Lima's coastal desert, goats are primarily fed on agricultural residues, whereas in the

Andean shrublands of Ancash they graze native shrubs, herbs, and grasses. The CFP associated with these distinct feeding strategies has not been quantified, either for goat systems or for other ruminant production systems in Peru. Given the marked differences in feed resources and environmental conditions between regions, which may influence milk composition, we hypothesized that differences in emissions intensity would emerge between systems.

Against this background, the present study assessed and compared the carbon footprint of goat farming under two contrasting grazing conditions found in neighboring regions: a crop-residue-based system in the coastal region of Lima and a native shrubland-based system in the Andean region of Ancash, Peru. Assessments were conducted seasonally within a year production cycle using collaborating farms from each region.

2. Materials and methods

2.1. Study location

The study was conducted in the regions of Lima and Ancash, Peru, spanning coordinates from 5°31'26.4" S, 79°58'55.2" W to 11°36'25.2" S, 77°12'54" W. The surveyed districts included Huaral, Aucallama, Santa María, and Huaura in the Lima region, and Huayllacayán, Pararín, Ocos, and Antonio Raymondi in the Ancash region (Fig. 1). Within these districts, goat farming is predominantly practiced across coastal desert ecosystems, Andean shrublands, and agricultural landscapes (MINAM, 2019).

Farms in the Lima region were located at elevations ranging from 45 to 189 m.a.s.l., whereas those in Ancash were situated between 1645 and 3633 m.a.s.l., reflecting the pronounced altitudinal gradient between coastal and Andean production systems. The goat populations within the study areas comprised 160,346 head in Lima and 168,104 head in Ancash, managed by approximately 13,082 and 3704 goat farmers, respectively (SIEA-MINAGRI, 2025).

Ancash, located in central-western Peru, exhibits pronounced altitudinal heterogeneity, ranging from coastal plains to high Andean and glaciated zones, resulting in 16 distinct climate types. In the mountainous areas where the study was conducted, temperatures range from 1 to 22 °C, with an average annual precipitation of 861 mm (SENAMHI, 2021). Seasonal patterns are clearly defined, with winter corresponding to the dry season and summer to the wet season, reflecting regional precipitation dynamics.

Similarly, the Lima region, situated on the central western slopes of the Andes, encompasses 12 climate types shaped by altitudinal gradients and maritime influence. The study area, located in Lima's coastal zone, is arid, with temperatures ranging from 13.5 to 26.7 °C and an average annual precipitation of 8 mm (SENAMHI, 2021).

2.2. Goat farming systems

This study examined two contrasting extensive goat production systems in Peru, distinguished by ecosystem and feeding resources. In the Lima region, goats rely primarily on crop residues, including maize, vegetables, sweet potato, and cotton (hereafter, the Lima system). Within the regional agricultural context, these residues are considered

low-economic-value secondary byproducts of the primary harvest. Consequently, they were treated as burden-free inputs in inventory. Accordingly, because these post-harvest residues remain in situ as rooted plant material and uncollected aboveground biomass, the only environmental burdens attributed to their use were those arising from direct grazing by goats, namely enteric fermentation and manure deposition. Diets based on crop residues are typically variable in protein content and high in fiber, often exhibiting lower digestibility than conventional diets (Shah et al., 2025). In contrast, systems in the Ancash region are based on extensive grazing of native shrubs, grasses, and herbaceous species typical of Andean shrublands (hereafter, the Ancash system) (Corredor et al., 2025; Paredes Chocce et al., 2024; Sifuentes et al., 2014). Shrubland-based diets are characterized by high botanical diversity and a richness in bioactive compounds that can influence ruminant metabolism. However, their nutritional quality and availability are strongly shaped by seasonal and environmental conditions, leading to marked intra-annual variability (Al Rharad et al., 2025; Patra and Saxena, 2011).

These systems represent structurally distinct production models in terms of feed sourcing, resource use, climate conditions, local animal adaptations and ecosystem interaction, providing an appropriate framework for comparative CFP assessment.

2.3. Carbon footprint analysis

Carbon footprint estimation followed an updated global methodological framework (International Dairy Federation, 2022). To ensure methodological clarity, the specific contribution of each reference

framework was defined as follows: ISO 14040 and ISO 14044 established the four-phase structure of the life cycle assessment (goal and scope definition, inventory analysis, impact assessment, and interpretation); ISO 14067 provided guidance for carbon footprint quantification; and the Greenhouse Gas Protocol informed the general principles of greenhouse gas accounting. Within this overarching LCA framework, the IDF guidelines were specifically applied to dairy-system modelling decisions, including the definition of the functional unit and the allocation of environmental burdens among coproducts. A cradle-to-farm-gate approach was used to quantify GHG emissions associated with milk production across the 12 evaluated farms, comprising six farms from each goat production system. The life cycle stages considered in the assessment are described in the following sections.

2.4. System boundaries

Fig. 2 depicts the system boundaries and the main input and output flows considered in the analysis. Within these boundaries, emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) were quantified across all stages included in the ‘cradle-to-farm gate’ approach, following updated guidelines (International Dairy Federation, 2022). This delimitation enabled the identification and attribution of emission sources associated with both on-farm production processes and external inputs (e.g., fuel and electricity) used by each production unit.

A critical modelling decision concerned the treatment of crop residues within the life cycle inventory. As these residues were considered burden-free, all upstream environmental burdens associated with crop production, including fertilizer use, irrigation, and land occupation,

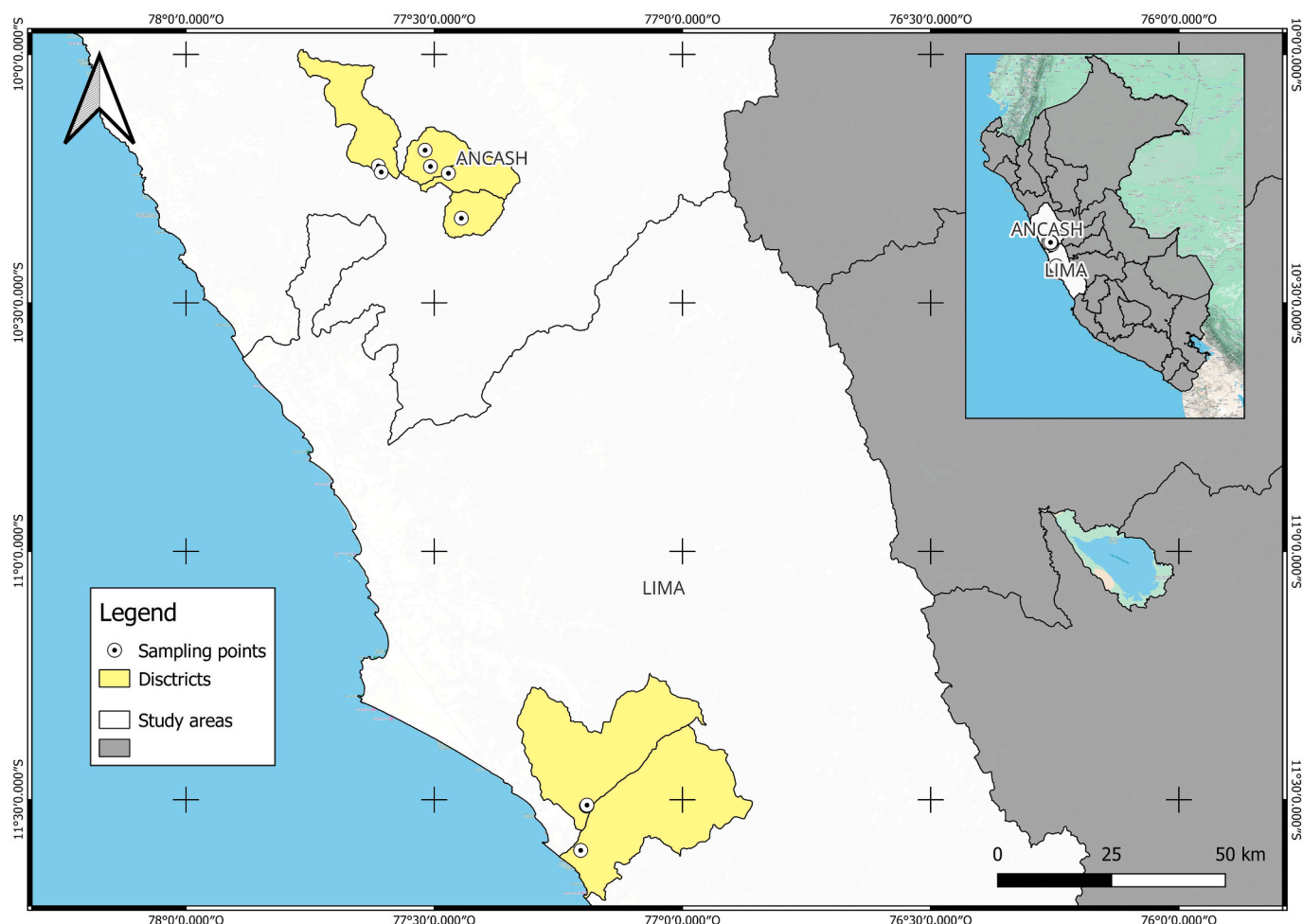


Fig. 1. Map of the study area and sampling points in Lima and Ancash regions.

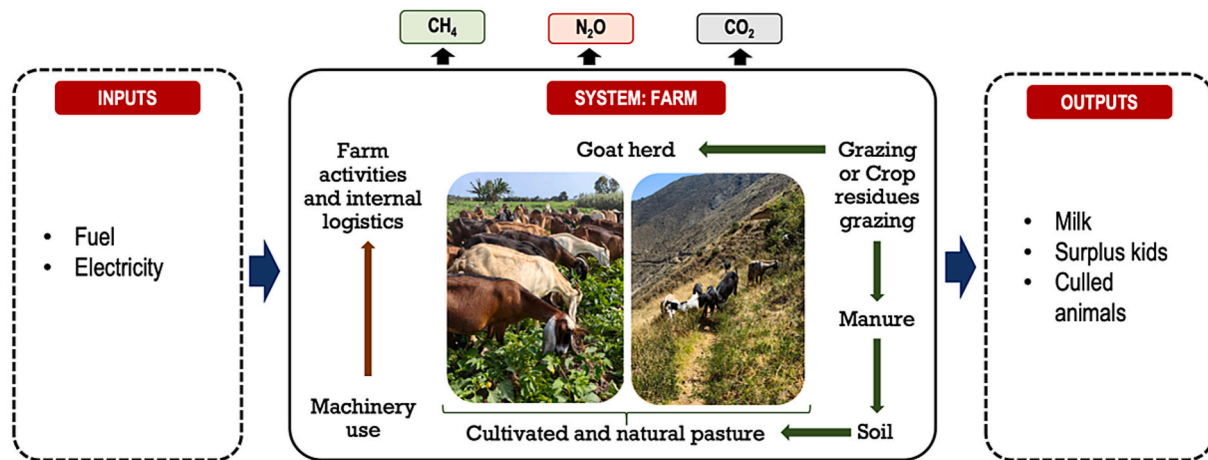


Fig. 2. System boundaries of the goat milk production system: A ‘cradle-to-farm gate’ approach in Lima and Ancash regions.

were allocated to the primary crop. Because goats graze residues directly in the field after harvest, the inventory includes only the emissions associated with their utilization, namely enteric fermentation and manure deposition during grazing.

Furthermore, impacts from land-use change were excluded by design, as the evaluated farms operate on long-standing native shrublands or established agricultural landscapes without recent conversion events. Finally, a methodological distinction was made for nitrogen excretion: manure deposited directly on pastures or fields during grazing was accounted for as direct and indirect N_2O emissions from managed soils, while manure handled in storage or housing was categorized strictly under manure management emissions, following Tier 2 IPCC specifications.

2.5. Functional units

The functional unit (FU) was defined as 1 kg of fat- and protein-corrected milk (FPCM), standardized to 4% fat and 3.3% protein, in accordance with current guidelines (International Dairy Federation, 2022) (Eq. 1). The use of FPCM allows for meaningful comparisons among dairy production systems by accounting for variations in milk composition. FPCM was calculated using:

$$\text{FPCM (Kg/year)} = \text{MY (Kg/year)} \times [0.1226 \times \text{F\%} + 0.0776 \times \text{P\%} + 0.2543] \quad (1)$$

where MY is milk yield, F is milk fat and P is milk protein.

2.6. Allocation of coproducts

Goat farming systems generate coproducts in addition to milk, including meat from surplus kids and culled animals. To ensure full consistency with the updated global methodological standards for dairy carbon footprint assessment (International Dairy Federation, 2022), environmental burdens were allocated among products using a biophysical allocation approach based on energy requirements, rather than a simple physical mass ratio. The allocation factor for milk (AF_{milk}) was calculated using the standard IDF equation:

$$AF_{\text{milk}} = 1 - 5.7717 \times (M_{\text{meat}}/M_{\text{milk}}) \quad (2)$$

Where M_{meat} is the sum of the live weight (kg) of all animals sold or culled, M_{milk} is the total amount of milk produced (kg FPCM), and 5.7717 is the standard constant representing the energy-requirement ratio between meat and milk production. This calculated AF_{milk} was then multiplied by the total farm greenhouse gas emissions to accurately isolate the environmental burden attributable solely to the milk.

Milk allocation factors averaged 0.92 (range: 0.89–0.94) in the Lima

system and 0.86 (range: 0.55–0.95) in the Ancash system across both seasons. The greater variability observed in Ancash reflected differences in herd size among farms. In particular, one smallholder farm (26 goats, compared with 161–502 goats in the remaining five farms) exhibited a substantially lower allocation factor (0.55–0.61), as animal sales accounted for a proportionally larger share of total farm output than milk production.

2.7. Data collection

Data were collected from 12 dairy goat farms located in the Lima and Ancash regions using structured surveys and standardized recording forms (Supplementary Table 1). Because no previous estimates of GHG emissions from Peruvian goat systems were available, sample size was determined using a two-group mean comparison approach (power = 95%, $\alpha = 0.05$), informed by effect sizes reported for extensive production systems operating in comparable, though not identical, geographic contexts (Gutiérrez-Peña et al., 2019). Farms were selected through a purposive, non-probabilistic sampling approach intended to capture system diversity, while also considering owner willingness to participate. Given the challenging environments in which goat systems operate, inclusion was limited to farms accessible by vehicle, with mobile communication coverage, and that had benefited from at least one state support or extension program. Only farms in which goat production was the primary activity and with animals in active milk production were included, irrespective of farm size, to capture herd diversity. Consequently, the evaluated farms are representative of accessible production contexts, but may not capture the full heterogeneity of goat farming systems across the study regions. Surveys were administered anonymously, participation was voluntary, and oral informed consent was obtained; no sensitive personal data were collected, and no experimental interventions were performed, therefore ethical approval was not required. Surveys were conducted during both winter and summer to capture seasonal variation within each production system.

The questionnaire gathered general information at the production-unit level. Livestock data collected included herd structure (number of animals by category), milk production ($\text{kg animal}^{-1} \text{ day}^{-1}$), and related production variables were collected. Diet and milk samples were collected during winter and summer assessments. Diets were sampled using a hand-plucking approach to approximate goat grazing, following the same procedure applied in woodland systems (Manousidis et al., 2016). Proximate analyses were conducted according to AOAC methods (950.46, 984.13, 2003.05, 962.09, and 942.05), and in vitro dry matter digestibility was determined using a standard procedure (Tilley and Terry, 1963). All laboratory analyses were performed at the Laboratorio de Evaluación Nutricional de Alimentos (LENA),

Universidad Nacional Agraria La Molina, Lima, Peru. Milk samples were collected seasonally and pooled in every farm. Composite samples were aliquoted (100 mL in sterile containers with three drops of formalin), stored at 4 °C, and analyzed by Fourier-transform infrared spectroscopy (FTIR) using a MilkoScan FT1 (FOSS, Denmark), following previously reported applications in goats (Li et al., 2022).

Agricultural management data encompassed crop or pasture area, grazing system, fertilizer type, origin, frequency and application rate, soil mechanization, and irrigation availability. Manure management practices, including storage method, waste handling, and ambient temperature, were also recorded. Technological inputs were documented, including the milking system (manual or mechanical) and the use of transport, fuel, and electricity.

2.8. Greenhouse gas estimation

The estimation of GHGs was performed using Tier II equations from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, in conjunction with the 2019 Refinement to the 2006 IPCC Guidelines (IPCC, 2019a, 2019b). Carbon dioxide (CO₂), biogenic methane (CH₄), and nitrous oxide (N₂O) emissions were expressed as carbon dioxide equivalents (CO₂-eq) using the following 100-year global warming potential (GWP₁₀₀) characterization factors: 1 kg CO₂ = 1 kg CO₂-eq, 1 kg CH₄ = 27.2 kg CO₂-eq, and 1 kg N₂O = 273 kg CO₂-eq (IPCC, 2021).

Emission factors corresponding to each emission source and system type were selected from the IPCC guidelines (IPCC, 2019c, 2019a, 2019b) and Ecoinvent® database (Table 1). To ensure full methodological transparency and reproducibility in compliance with ISO 14044 requirements, a detailed description of the calculation pathways, including the specific equations, assumptions, and parameter sources used to model enteric CH₄, manure CH₄, nitrogen excretion, and direct and indirect N₂O emissions, is provided in Supplementary Methods 1.

2.9. Data analysis

Data processing and analysis were carried out using Microsoft® Excel® LTSC MSO. Statistical analyses were performed using RStudio statistical software (R Core Team, 2024). Normality and homogeneity of variances were assessed for all the variables under study. Comparisons of farm characteristics between production systems within each season were conducted using Student's *t*-test when parametric assumptions were met; otherwise, the Mann–Whitney *U* test was applied.

Emissions data were analyzed using a linear mixed-effects model fitted by restricted maximum likelihood (REML):

$$Y = X_1 * X_2 + (1|F)$$

where *Y* represented the emission response variable; *X*₁ and *X*₂ corresponded to the fixed effects of production system (region) and season, respectively; and *X*₁ × *X*₂ denoted their interaction. Farm (*F*) was included as a random intercept effect, specified as (1*F*), to account for repeated observations within farms. Random slopes were not incorporated because the seasonal factor comprised only two repeated levels, providing insufficient replication to reliably estimate between-farm variation in temporal slopes. Statistical significance of fixed effects was assessed using *t*-tests, and marginal significance was declared at $\alpha = 0.05$.

3. Results

3.1. Farm characteristics

Farm population, structure, diet composition, and milk characteristics are presented to describe the differences between the production systems and seasons. (Table 2).

Winter. No statistically significant differences were detected

Table 1

Emission factors used to estimate the greenhouse gas (GHG) emissions for each farm in the study.

Emission category	Type of GHG	Emission factor	Unit	Source
Enteric fermentation				
Maintenance coefficient	CH ₄	0.315	MJ kg ⁻¹ W ^{0.75} day ⁻¹	(IPCC, 2019a)
Activity coefficient (Ca) - Lima	CH ₄	0.019	MJ kg ⁻¹ day ⁻¹	(IPCC, 2019a)
Activity coefficient (Ca) - Ancash	CH ₄	0.024	MJ kg ⁻¹ day ⁻¹	(IPCC, 2019a)
Pregnancy coefficient (Cpe)	CH ₄	0.126	dimensionless	(IPCC, 2019a)
Energy value of milk (EVmilk)	CH ₄	3	MJ kg ⁻¹ milk	(IPCC, 2019a)
Methane conversion factor (Ym)	CH ₄	5.5 ± 1.0	% of gross energy intake	(IPCC, 2019a)
Energy content of methane	CH ₄	55.65	MJ kg ⁻¹ CH ₄	(IPCC, 2019a)
Manure management				
Direct N ₂ O, from manure solid storage	N ₂ O	0.010	kg N ₂ O-N / kg N excreted	(IPCC, 2019a)
Direct N ₂ O, from pasture/range/paddock	N ₂ O	0.003	kg N ₂ O-N / kg N excreted	(IPCC, 2019b)
Indirect N ₂ O, volatilization from soil	N ₂ O	0.010	kg N ₂ O-N / kg N volatilized	(IPCC, 2019a)
Indirect N ₂ O, leaching/runoff from soil	N ₂ O	0.011	kg N ₂ O-N / kg N leaching/runoff	(IPCC, 2019a)
Fuel				
Gasoline	CH ₄	33	kg CO ₂ -eq/TJ	(IPCC, 2019b)
	N ₂ O	3.2	kg CO ₂ -eq/TJ	(IPCC, 2019b)
Oil	CO ₂	63,100	kg CO ₂ -eq/TJ	(IPCC, 2019b)
Lubricant	CO ₂	73,300	kg CO ₂ -eq/TJ	(IPCC, 2019b)
Electricity use (production)	CO ₂	0.006585	kg CO ₂ -eq/kWh	Ecoinvent v3.6 (Allocation, cut-off)
Electricity use (distribution)	CO ₂	0.002897	kg CO ₂ -eq/kWh	Ecoinvent v3.6 (Allocation, cut-off)

between systems during winter. However, several variables showed numerical differences approaching significance. Herd size tended to be greater in Ancash ($p = 0.065$), whereas goats from the Lima system exhibited numerically higher body weight in production (55.38 vs. 48.96 kg; $p = 0.065$). Diet composition also showed numerical variation between systems, with lower crude protein content in Ancash (10.26%) than in Lima (13.15%), and higher neutral detergent fiber (NDF) concentrations in Ancash (44.1%) than in Lima (40.9%). These patterns reflect contrasting feeding sources and nutrient profiles, based primarily on horticultural crop residues in Lima and on shrubs and herbaceous species from Andean shrublands in Ancash. Milk composition showed similar non-significant tendencies: milk fat content was higher in Lima (5.89%) than in Ancash (4.87%), as was total solids content (14.95% vs. 13.23%; $p = 0.066$), although these differences did not reach statistical significance (Table 2).

Summer. Consistent with winter observations, system-level differentiation was more pronounced during the summer season, reaching statistical significance for several parameters. Average farm population size was numerically higher in Ancash than in Lima (271 vs. 106 head; p

Table 2

Farm characteristics (herd attributes, diet, and milk composition) by farming system and season. Means were compared using Student's *t*-test; when normality assumptions were not met, the Mann–Whitney *U* test was applied (†). Statistical thresholds are denoted as follows: #, $p < 0.1$ (shown for descriptive purposes only); *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Season	Winter			Summer		
	Ancash	Lima	<i>p</i> -value	Ancash	Lima	<i>p</i> -value
Herd Characteristics						
Goat						
population /farm (heads)	255.33	97.00	0.066 ^{#†}	271.67	106.33	0.066 ^{#†}
Lactating goats/ farm (heads)	142.17	49.67	0.128 [†]	150.17	53.50	0.109 [†]
Body weight of dairy goats (kg)	48.96	55.38	0.066 ^{#†}	50.52	55.97	0.093 ^{#†}
Average daily milk production per goat (kg)	1.24	1.44	0.102 [†]	1.43	1.63	0.102 [†]
Nutritional content of the diet						
Crude protein (%)	10.26	13.15	0.077 ^{#†}	11.59	13.56	0.045*
Neutral Detergent Fiber (FDN) (%)	44.1	40.96	0.195	42.65	33.10	<0.001***
In Vitro Dry Matter Digestibility of Dry Matter (IVDMD) (%)	60.31	59.65	0.665	64.50	64.35	0.904
Milk composition						
Fat content in milk (%)	4.87	5.89	0.093 ^{#†}	6.32	4.58	0.0022**
Protein content in milk (%)	4.05	4.24	0.645	4.33	4.18	0.478
Non fat solids in milk (%)	8.36	9.06	0.100	9.06	9.14	0.787
Total solids in milk (%)	13.23	14.95	0.066 ^{#†}	15.38	13.70	0.021*
Lactose in milk (%)	3.96	4.26	0.936 [†]	4.16	4.29	0.606

= 0.065), although the difference was not statistically significant. Likewise, body weight of animals in production remained numerically greater in Lima (55.97 vs. 50.52 kg; $p = 0.093$). Diet composition differed markedly, with significantly higher crude protein content in the Lima system (13.56%) compared with Ancash (11.59%; $p < 0.05$), and higher NDF levels in Ancash (42.65%) than in Lima (33.10%; $p < 0.001$). In contrast to winter trends, milk composition also differed significantly: the Ancash system exhibited higher milk fat content (6.3%) than Lima (4.6%; $p < 0.01$), accompanied by greater total solids content (15.38% vs. 13.70%; $p < 0.05$).

3.2. Carbon footprint

The annual carbon footprint (CFP; kg CO₂-eq kg⁻¹ FPCM) is presented as a descriptive, source-specific emissions profile, calculated as the mean across farms within the Ancash and Lima production systems (Table 3). The Ancash shrubland-based system exhibited an average CFP of 1.038 kg CO₂-eq kg⁻¹ FPCM, with enteric fermentation representing the dominant emission source, accounting for 74% of total emissions,

Table 3

Carbon footprint in kg of CO₂-eq kg⁻¹ of fat and protein corrected milk (FPCM) broken down by emission source for Lima and Ancash production systems in 2023–2024.

Emission source	System	
	Ancash	Lima
Total emission for Enteric Fermentation	0.774	0.914
Total emission for Manure management	0.092	0.109
Manure management (CH ₄ emission)	0.041	0.051
Manure management (direct N ₂ O emission)	0.032	0.038
Manure management (indirect N ₂ O emission by leaching)	0.017	0.018
Manure management (indirect N ₂ O emission by volatilization)	0.001	0.002
Total emission for Fuel usage	0.089	0.054
Fuel usage (CO ₂)	0.087	0.053
Fuel usage (CH ₄)	0.001	0.001
Fuel usage (N ₂ O)	0.001	0.001
Total emission for Electricity use	0.084	0.078
Total emissions	1.038	1.155

followed by manure management (9%), fuel use (9%), and electricity consumption (8%). In the Lima crop residue-based system, the CFP averaged 1.155 kg CO₂-eq kg⁻¹ FPCM, of which 79% originated from enteric fermentation, while manure management, fuel use and electricity consumption contributed 9%, 5%, and 7%, respectively. When manure management emissions were disaggregated, methane accounted for 44.6% of total manure-related emissions in Ancash, with the remainder attributable to direct and indirect nitrous oxide emissions. A comparable pattern was observed in Lima, where methane represented 46.8% of manure management emissions. Regarding fuel use, carbon dioxide constituted 97.8% of fuel-related emissions in Ancash and 98.1% in Lima. The underlying daily, farm-level greenhouse gas emissions used to derive FPCM-corrected values are detailed in Supplementary Table 2.

Overall, total emissions across farms and seasons ranged from 0.671 to 1.538 kg CO₂-eq kg⁻¹ FPCM (Fig. 3A,B). Emission values were comparatively more homogeneous among farms during winter (Fig. 3A) than during summer (Fig. 3B), consistent with the patterns reported in Supplementary Table 3. A greater visual separation between system means was observed during summer (Fig. 3C,D); however, mixed-effects modelling indicated no significant differences in total CFP between systems.

Therefore, mixed-effects modelling of GHG emissions by major source indicated no significant differences between production systems (Table 4). When emissions were further partitioned by gas and emission process, a minimal difference was detected only for indirect N₂O emissions from volatilization ($p = 0.0327$), which were higher in the Lima system (0.002 vs 0.001 kg CO₂-eq kg⁻¹ FPCM). Even for enteric fermentation, where numerical differences between systems were observed, the estimated marginal means (EMMs) confidence intervals (CIs) showed substantial overlap, ranging from 0.705 to 1.122 kg CO₂-eq kg⁻¹ FPCM in Lima, and 0.512–1.037 kg CO₂-eq kg⁻¹ FPCM in Ancash (Table 5). In contrast, significant seasonal effects were detected for enteric fermentation ($p = 0.0002$) and manure management emissions ($p = 0.0042$), which together contributed to seasonal variation in total CFP ($p = 0.0002$) (Table 4). Specifically, EMMs for total CFP ranged from 0.724 to 1.266 kg CO₂-eq kg⁻¹ FPCM during summer to 1.013–1.384 kg CO₂-eq kg⁻¹ FPCM during winter (Table 5).

Moreover, significant system × season interactions were observed for emissions associated with fuel use ($p = 0.0084$) and electricity consumption ($p = 0.0174$) (Table 4). Detailed EMMs presented in Table 5 further illustrate these interaction patterns. Numerically, fuel-related emissions in Ancash increased from summer to winter (0.081 to 0.096 kg CO₂-eq kg⁻¹ FPCM), whereas in Lima they slightly declined from 0.057 to 0.052 kg CO₂-eq kg⁻¹ FPCM. A similar contrasting seasonal pattern was observed for electricity-related emissions, which increased in Ancash (0.070 to 0.097 kg CO₂-eq kg⁻¹ FPCM) but

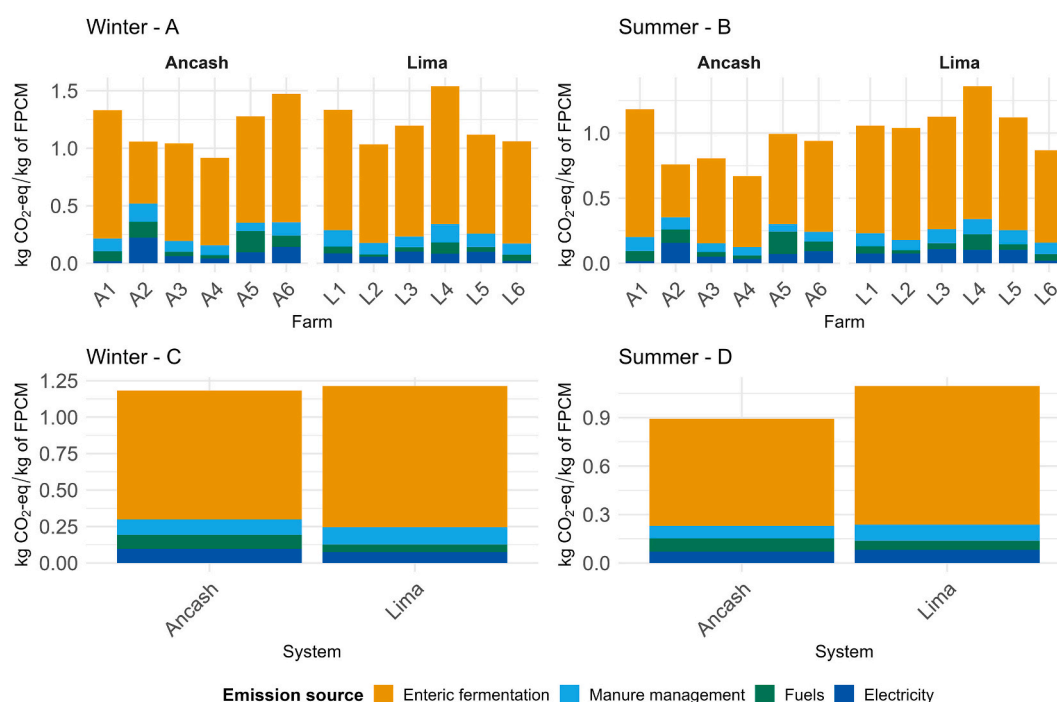


Fig. 3. Carbon footprint in kg of CO₂-eq kg⁻¹ of fat and protein corrected milk (FPCM) broken down by emission source per farm (A and B) and per System (C and D). Ancash system is based on Andean shrublands, while Lima system is based on crop residues.

Table 4

Significance of fixed effects after linear mixed-effects modelling of the carbon footprint in kg of CO₂-eq kg⁻¹ of fat and protein corrected milk (FPCM), broken down by emission source for Lima and Ancash production systems during winter and summer seasons. Statistical significance for $p < 0.05$.

Emission source	P-value per fixed effects		
	System	Season	System × season
Total emission for Enteric Fermentation	0.1620	0.0002	0.0872
Total emission for Manure management	0.1808	0.0042	0.4953
Manure management (CH ₄ emission)	0.1650	0.0003	0.2342
Manure management (direct N ₂ O emission)	0.2216	0.0955	0.8434
Manure management (indirect N ₂ O emission by leaching)	0.5992	0.0801	0.7664
Manure management (indirect N ₂ O emission by volatilization)	0.0327	0.1088	0.9672
Total emission for Fuel usage	0.2079	0.1349	0.0084
Fuel usage (CO ₂)	0.2063	0.1336	0.0083
Fuel usage (CH ₄)	0.3573	0.1988	0.0138
Fuel usage (N ₂ O)	0.3573	0.1988	0.0138
Total emission for Electricity use	0.8415	0.1128	0.0174
Total emissions	0.2804	0.0002	0.0349

decreased in Lima (0.081 to 0.075 kg CO₂-eq kg⁻¹ FPCM) (Fig. 4).

4. Discussion

Goats exhibit a suite of morphological, physiological and metabolic adaptations that confer resilience to harsh conditions, including high solar radiation, water scarcity and plant defenses, often surpassing other livestock species (Kolman Darcán, 2023). However, advantages in terms of GHG emissions are context-dependent and vary with the production system and comparator species. For instance, across livestock systems in different Indian states, goats showed either higher or lower emissions per kg of milk, milk protein or milk energy depending on location, although emissions were generally lower than those of indigenous cows and higher than those of crossbred cows and buffaloes (Patra, 2017). Similarly, a comparison of semi-extensive dairy systems

in Greece reported lower emissions per kg of FPCM for goats than for sheep (Laliotis and Bizelis, 2025). While goats are considered to emit less GHG per unit of body weight than other domestic ruminants (Kolman Darcán, 2023), these intrinsic differences appear secondary to the combined effects of system-level inputs and outputs.

In the present study, the CFP of goat production systems in Lima and Ancash ranged from 0.671 to 1.538 kg CO₂-eq kg⁻¹ FPCM, values consistent with those reported globally despite substantial variation in production systems. In southern Spain, emissions from goat systems with differing degrees of intensification ranged from 1.04 to 3.17 kg CO₂-eq kg⁻¹ FPCM (Gutiérrez-Peña et al., 2019; Horrillo et al., 2020; Mancilla-Leytón et al., 2023; Pardo et al., 2016), whereas lower CFP values (0.65–1.19 kg CO₂-eq kg⁻¹ FPCM) have been reported in New Zealand, even in systems based on cultivated forages (Robertson et al., 2015). Although direct comparisons across studies are constrained by differences in functional units, system boundaries and allocation methods (Bernués et al., 2017; Joly et al., 2024), these results collectively define a plausible range of emissions for dairy goat systems. Goat farming systems in Lima and Ancash differ markedly in climate, management and feeding strategies, relying primarily on crop residues and Andean shrublands, respectively. Such characteristics have been identified as key drivers of emission variability, even within the same geographic context (Kerven, 2024). Nevertheless, both systems exhibited comparable overall CFP. The only significant difference was a small increase in indirect N₂O emissions from manure management via volatilization in the Lima system. Given the higher dietary N concentrations in Lima, this pattern may reflect greater N excretion (Devant et al., 2022), although this mechanism remains to be confirmed. Comparative analyses between contrasting extensive systems remain uncommon in the literature, which more frequently contrasts extensive and intensive production models. Although crop residues are widely recognized as an important feed resource in goat production (Charambira et al., 2021; Montcho et al., 2025), the CFP of systems based exclusively on grazing crop residues has not yet been directly evaluated. GLEAM assessments suggest that partial replacement of forages and fodders with crop residues can reduce GHG emissions in goat systems, while also indicating that high-grain diets are more effective in lowering methane

Table 5

Estimated marginal means [95% Confidence Interval] of carbon footprint in kg of CO₂-eq kg⁻¹ of fat and protein corrected milk (FPCM) broken down by emission source for Lima and Ancash production systems during winter and summer seasons.

Emission source	Summer		Winter	
	Lima	Ancash	Lima	Ancash
Total emission for Enteric Fermentation	0.858 [0.705–1.011]	0.663 [0.512–0.814]	0.969 [0.816–1.122]	0.884 [0.731–1.037]
Total emission for Manure management	0.099 [0.078–0.121]	0.078 [0.056–0.099]	0.119 [0.097–0.14]	0.106 [0.084–0.127]
Manure management (CH ₄ emission)	0.045 [0.034–0.057]	0.032 [0.021–0.043]	0.056 [0.045–0.068]	0.05 [0.039–0.061]
Manure management (direct N ₂ O emission)	0.035 [0.027–0.044]	0.029 [0.02–0.037]	0.04 [0.032–0.049]	0.035 [0.027–0.044]
Manure management (indirect N ₂ O emission by leaching)	0.017 [0.013–0.022]	0.015 [0.011–0.02]	0.02 [0.015–0.024]	0.019 [0.015–0.023]
Manure management (indirect N ₂ O emission by volatilization)	0.002 [0.001–0.002]	0.001 [0.001–0.002]	0.002 [0.002–0.003]	0.002 [0.001–0.002]
Total emission for Fuel usage	0.057 [0.016–0.097]	0.081 [0.041–0.122]	0.052 [0.011–0.092]	0.096 [0.056–0.137]
Fuel usage (CO ₂)	0.055 [0.016–0.095]	0.080 [0.040–0.120]	0.051 [0.011–0.090]	0.094 [0.054–0.134]
Fuel usage (CH ₄)	0.001 [0.000–0.001]	0.001 [0.000–0.001]	0.001 [0.000–0.001]	0.001 [0.000–0.001]
Fuel usage (N ₂ O)	0.001 [0.000–0.001]	0.001 [0.000–0.001]	0.001 [0.000–0.001]	0.001 [0.000–0.001]
Total emission for Electricity use	0.081 [0.035–0.127]	0.070 [0.025–0.116]	0.075 [0.029–0.120]	0.097 [0.051–0.143]
Total emissions	1.096 [0.925–1.266]	0.892 [0.724–1.061]	1.214 [1.043–1.384]	1.183 [1.013–1.354]

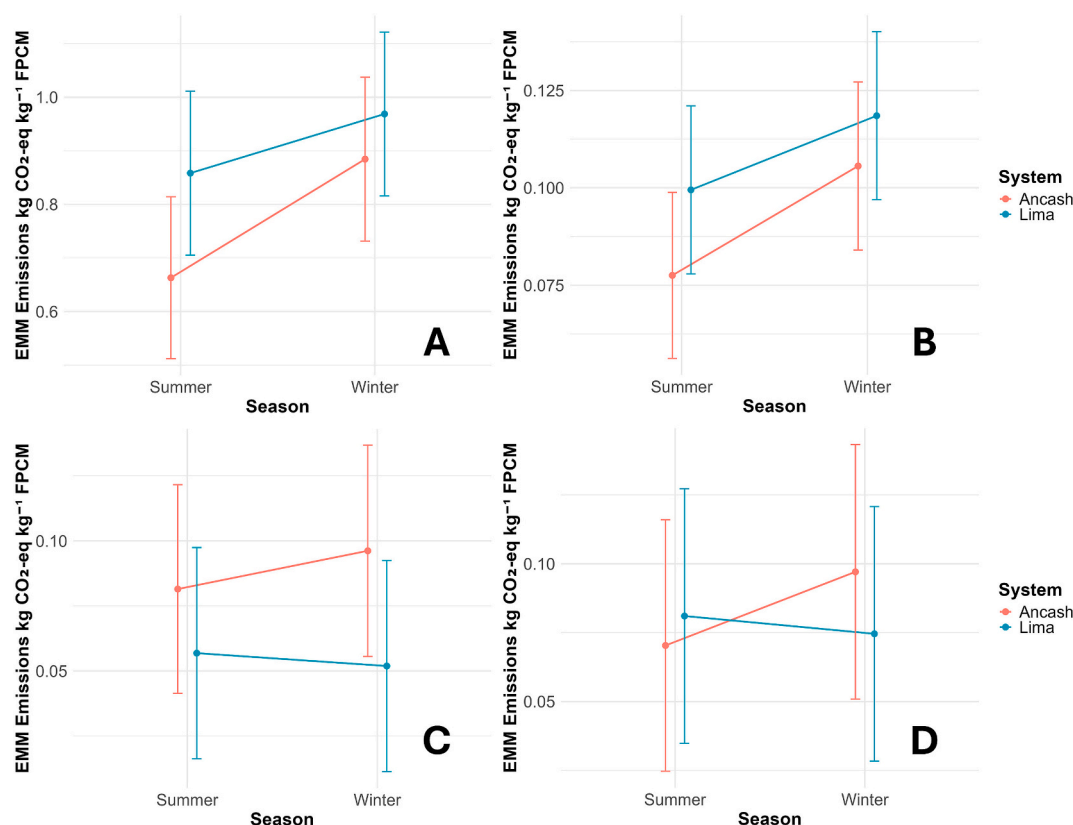


Fig. 4. System × season interaction plots showing the estimated marginal means (EMMs) of emissions (kg CO₂-eq kg⁻¹ fat- and protein-corrected milk [FPCM]) from enteric fermentation (A), manure management (B), fuel use (C), and electricity use (D). Bars show 95% Confidence Intervals.

emissions per unit of product (Salami et al., 2019), although the latter was not evaluated in the present study. However, comparable CFPs have been reported between shrubland-based autochthonous goat systems and more intensified production systems, despite marked differences in feeding strategies and management (Mancilla-Leytón et al., 2023).

In contrast to production system effects, season emerged as a major determinant of carbon footprint variation, with enteric fermentation accounting for most of the seasonal differences in emissions. Although seasonal estimates of enteric emissions are rarely reported, studies in rangeland cattle have shown that, when evaluated independently of

other grazing-system factors, seasonal variation in forage quality and availability accounts for a substantial proportion of the differences in enteric emissions between seasons, although environmental conditions and grazing management also contribute (Gbenou et al., 2024). The present findings are consistent with observations from Andean dairy systems, where enteric methane emission per energy-corrected milk were greater during winter than summer (Alvarado-Bolovich et al., 2021). Moreover, significant system $\times$ season interactions were detected for disaggregated emission sources, indicating that seasonal responses differed between production contexts. Specifically, emissions associated with fossil fuel and electricity use declined from summer to winter in the Lima system, whereas the opposite trend was observed in Ancash. A plausible explanation is that winter drought and frost conditions in the Andean region reduce the availability of accessible grazing areas, thereby forcing farmers to travel longer distances with their herds in search of forage resources (López-i-Gelats et al., 2015). Drought context may also increase reliance on electrically powered water extraction systems for farm households, contributing to greater fuel and electricity consumption. Nevertheless, these explanations remain hypothetical and warrant direct empirical evaluation.

Herd characterization within seasons revealed compositional and dietary differences between systems during the summer, which may accompany CFP variability. During summer, goats in Ancash produced milk with higher fat and total solids than those in Lima, as it happened in other mountain systems with goat local breeds (Delgadillo-Puga and Cuchillo-Hilario, 2021; Mancilla-Leytón et al., 2013), despite comparable milk yield and diet digestibility. Shrub-based diets in Ancash also exhibited higher NDF levels which may have promoted acetate production and subsequent milk fat if dietary energy and protein requirements were met (Lu et al., 2005; Mele et al., 2005; Morand-Fehr et al., 2007). Despite compositional differences in food source and milk, CFP remained similar between systems, following evidence from other studies where even having distinct food source input and milk yield, CFP resulted comparable (Gutiérrez-Peña et al., 2019; Mancilla-Leytón et al., 2013). The comparable CFP observed between systems may be associated with the absence of marked differences in digestibility and milk yield, both of which influence enteric-emission estimates.

Notwithstanding the overall similarity in CFPs between the two goat production systems evaluated, several limitations should be acknowledged. Digestibility estimates were derived from *in vitro* analyses of the diets which may not fully capture region-specific metabolic adaptations of the animals (Assouma et al., 2025; Ravhuhali et al., 2022). Carbon sequestration was not quantified; consequently, the results are limited to product CFP and do not capture net ecosystem climate impacts, which may differ between grazing and cropping ecosystems (Teague et al., 2016). The potential of secondary plant compounds, such as condensed tannins from shrubs, to modulate enteric emissions was not considered (Animut et al., 2008; Seidavi et al., 2020), highlighting the importance of this component in future assessments.

5. Conclusions

Despite marked differences in environmental conditions, feed resources and milk composition between the crop residue-based system in Lima and the shrubland-based system in Ancash, both exhibited comparable carbon footprint, with enteric fermentation remaining the predominant source of greenhouse gas emissions. Significant system $\times$ season interactions for fuel and electricity emissions revealed context-dependent resource-use patterns beyond the effects of seasonality alone, highlighting the complexity of emissions dynamics in extensive goat production. As the first carbon footprint assessment of Peruvian Creole goat systems, this study establishes a benchmark for evaluating environmental sustainability and underscores the need to quantify how environmental heterogeneity and management practices shape emissions across diverse production systems.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to correct the manuscript for style. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Richard Ayala Roldan: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miguel Paredes-Chocce:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hugo Castillo Dolori:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **David Godoy-Padilla:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Juancarlos Alejandro Cruz-Luis:** Writing – review & editing, Resources, Methodology, Conceptualization. **José Antonio Haro-Reyes:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization.

Funding

This study was supported by the INIA Investment Project: “Mejoramiento de los servicios de investigación y transferencia de tecnologías para el manejo sostenible de la ganadería caprina en bosque seco, en los departamentos de Tumbes, Piura, Lambayeque, Amazonas, La Libertad, Ancash, Ayacucho, Ica y Lima” with CUI N° 2506684.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agry.2026.104993>.

Data availability

Data will be made available on request.

References

- Al Rharad, A., El Aayadi, S., Avril, C., Souradjou, A., Sow, F., Camara, Y., Hornick, J.-L., Boukrouh, S., 2025. Meta-analysis of dietary tannins in small ruminant diets: effects on growth performance, serum metabolites, antioxidant status, ruminal fermentation, meat quality, and fatty acid profile. *Animals* 15, 596. <https://doi.org/10.3390/ani15040596>.
- Alvarado-Bolovich, V., Medrano, J., Haro, J., Castro-Montoya, J., Dickhoefer, U., Gómez, C., 2021. Enteric methane emissions from lactating dairy cows grazing cultivated and native pastures in the high Andes of Peru. *Livest. Sci.* 243, 104385. <https://doi.org/10.1016/j.livsci.2020.104385>.
- Animut, G., Puchala, R., Goetsch, A.L., Patra, A.K., Sahl, T., Varel, V.H., Wells, J., 2008. Methane emission by goats consuming diets with different levels of condensed tannins from lespedeza. *Anim. Feed Sci. Technol.* 144, 212–227. <https://doi.org/10.1016/j.anifeeds.2007.10.014>.
- Assouma, M.H., Lecomte, P., Hiernaux, P., Ickowicz, A., Decruyenaere, V., Blanchard, M., Wade, C., Bois, B., Corniaux, C., Guichard, F., Vayssières, J., 2025. Seasons, herd mobility and management drive feed intake and digestibility in grazing cattle in West African landscapes. *Front. Anim. Sci.* 6, 1681640. <https://doi.org/10.3389/fanim.2025.1681640>.
- Bartl, K., Gómez, C.A., Nemecek, T., 2011. Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru. *J. Clean. Prod.* 19, 1494–1505. <https://doi.org/10.1016/j.jclepro.2011.04.010>.

- Bernués, A., Rodríguez-Ortega, T., Olaizola, A.M., Ripoll-Bosch, R., 2017. Evaluating ecosystem services and disservices of livestock agroecosystems for targeted policy design and management. In: *Grassland Resources for Extensive Farming Systems in Marginal Lands: Major Drivers and Future Scenarios*. Presented at the 19th Symposium of the European Grassland Federation. CNR-ISPAAM, Alghero, Italy, pp. 259–267.
- Charambira, T., Kagande, S.M., Chakoma, I., Chibaira, G., Mugabe, P.H., 2021. Goat feeds and feeding practises in a semi-arid smallholder farming system in Zimbabwe. *Afr. J. Range Forage Sci.* 38, S90–S93. <https://doi.org/10.2989/10220119.2021.1981444>.
- Corredor, F.-A., Godoy-Padilla, D., Sessarego, E.A., Temoche-Socla, V., Paredes Chocce, M.E., Escobar Robledo, H., Ramírez Antaurco, M.F., Burgos-Paz, W., Ruiz, J., Cruz, J., Mulim, H.A., Oliveira, H.R.D., 2025. Genomic characterization of Peruvian Creole goats: insights into population structure and runs of homozygosity. *Animals* 15, 2577. <https://doi.org/10.3390/ani15172577>.
- Cottle, D.J., Cowie, A.L., 2016. Allocation of greenhouse gas production between wool and meat in the life cycle assessment of Australian sheep production. *Int. J. Life Cycle Assess.* 21, 820–830. <https://doi.org/10.1007/s11367-016-1054-4>.
- Delgadillo-Puga, C., Cuchillo-Hilario, M., 2021. Reviewing the benefits of grazing/browsing semiarid rangeland feed resources and the transference of bioactivity and pro-healthy properties to goat milk and cheese: obesity, insulin resistance, inflammation and hepatic steatosis prevention. *Animals* 11, 2942. <https://doi.org/10.3390/ani11102942>.
- Devant, M., Pérez, A., Medinyà, C., Riera, J., Grau, J., Fernández, B., Prenafeta-Boldú, F. X., 2022. Effect of decreasing dietary crude protein in fattening calves on the emission of ammonia and greenhouse gases from manure stored under aerobic and anaerobic conditions. *Animal* 16, 100471. <https://doi.org/10.1016/j.animal.2022.100471>.
- Dubeuf, J.-P., Genis, J.C., Morand-Fehr, P., Ruiz Morales, F.D.A., 2023. The contribution of goats in the future redesigning of livestock activities and value chains. *Small Rumin. Res.* 227, 107065. <https://doi.org/10.1016/j.smallrumres.2023.107065>.
- FAO, 2022. *Greenhouse Gas Emissions from Agrifood Systems (Brief No. 50)*, Global, Regional and Country Trends, 2000–2020. FAOSTAT.
- FAO, 2023. Pathways towards lower emissions – a global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems. FAO, Rome. <https://doi.org/10.4060/cc9029en>.
- Gbenou, G.X., Assouma, M.H., Bastianelli, D., Kiendrebeogo, T., Bonnal, L., Zampaligre, N., Bois, B., Sanogo, S., Sib, O., Martin, C., Dossa, L.H., 2024. Enteric methane emissions from zebu cattle are influenced by seasonal variations in rangeland fodder quality and intake. *Animal* 18, 101320. <https://doi.org/10.1016/j.animal.2024.101320>.
- Gutiérrez-Peña, R., Mena, Y., Batalla, I., Mancilla-Leytón, J.M., 2019. Carbon footprint of dairy goat production systems: a comparison of three contrasting grazing levels in the Sierra de Grazalema Natural Park (Southern Spain). *J. Environ. Manag.* 232, 993–998. <https://doi.org/10.1016/j.jenvman.2018.12.005>.
- Horriño, A., Gaspar, P., Escribano, M., 2020. Organic farming as a strategy to reduce carbon footprint in dehesa agroecosystems: a case study comparing different livestock products. *Animals* 10, 162. <https://doi.org/10.3390/ani10010162>.
- International Dairy Federation, 2022. The IDF Global Carbon Footprint Standard for the Dairy Sector. International Dairy Federation (IDF) AISBL. <https://doi.org/10.56169/FKRRK7166>.
- IPCC, 2019a. Chapter 10: Emissions from livestock and manure management. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
- IPCC, 2019b. Chapter 11: N2O emissions from managed soils, and CO2 emissions from lime and urea application. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, p. 54.
- IPCC, 2019c. Chapter 3: Mobile Combustion. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
- IPCC, 2021. The earth's energy budget, climate feedbacks, and climate sensitivity. In: *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 923–1054. <https://doi.org/10.1017/9781009157896>.
- Joly, F., Roche, P., Fossey, M., Rebeaud, A., Dewulf, J., Van Der Werf, H.M.G., Boone, L., 2024. How closely do ecosystem services and life cycle assessment frameworks concur when evaluating contrasting animal-production systems with ruminant or monogastric species? *Animal* 18, 101368. <https://doi.org/10.1016/j.animal.2024.101368>.
- Kerven, C., 2024. Contribution of goats to climate change: how and where? *Pastor. Res. Policy Pract.* 14, 13988. <https://doi.org/10.3389/past.2024.13988>.
- Koluman Darcen, N., 2023. Goats and their role in climate change. *Small Rumin. Res.* 228, 107094. <https://doi.org/10.1016/j.smallrumres.2023.107094>.
- Laliotis, G.P., Bizelis, I., 2025. Assessment of greenhouse gas emissions and carbon footprint in mountainous semi-extensive dairy sheep and goat farms in Greece. *Environments* 12, 232. <https://doi.org/10.3390/environments12070232>.
- Li, S., Delger, M., Dave, A., Singh, H., Ye, A., 2022. Seasonal variations in the composition and physicochemical characteristics of sheep and goat milks. *Foods* 11, 1737. <https://doi.org/10.3390/foods11121737>.
- López Huamani, C.J., 2021. Composición e higiene en la leche de cabras saanen en crianza establecida y su efecto sobre el rendimiento quesero. Universidad Nacional Agraria La Molina, Lima, Peru.
- López-i-Gelats, F., Contreras Paco, J.L., Huilcas Huayra, R., Sigas Robles, O.D., Quispe Peña, E.C., Bartolomé Filella, J., 2015. Adaptation strategies of Andean pastoralist households to both climate and non-climate changes. *Hum. Ecol.* 43, 267–282. <https://doi.org/10.1007/s10745-015-9731-7>.
- Lu, C.D., Kawas, J.R., Mahgoub, O.G., 2005. Fibre digestion and utilization in goats. *Small Rumin. Res.* 60, 45–52. <https://doi.org/10.1016/j.smallrumres.2005.06.035>.
- Mancilla-Leytón, J.M., Vicente, A.M., Delgado-Perfínez, M., 2013. Summer diet selection of dairy goats grazing in a Mediterranean shrubland and the quality of secreted fat. *Small Rumin. Res.* 113, 437–445. <https://doi.org/10.1016/j.smallrumres.2013.04.010>.
- Mancilla-Leytón, J.M., Morales-Jerrett, E., Muñoz-Vallés, S., Mena, Y., 2023. A comparative analysis of carbon footprint in the Andalusian autochthonous dairy goat production systems. *Animals* 13, 2864. <https://doi.org/10.3390/ani13182864>.
- Manousidis, T., Kyriazopoulos, A.P., Parissi, Z.M., Abraham, E.M., Korakis, G., Abas, Z., 2016. Grazing behavior, forage selection and diet composition of goats in a Mediterranean woody rangeland. *Small Rumin. Res.* 145, 142–153. <https://doi.org/10.1016/j.smallrumres.2016.11.007>.
- Mele, M., Buccioni, A., Serra, A., 2005. Neutral Detergent Fibre (NDF) and Non Structural Carbohydrate (NSC) requirements in the nutrition of dairy ewes. *Ital. J. Anim. Sci.* 4, 45–52. <https://doi.org/10.4081/ijas.2005.1s.45>.
- MINAM, 2019. *Mapa Nacional de Ecosistemas del Perú*.
- Modi, R.J., Patel, N.M., Patel, Y.G., Islam, M.M., Nayak, J.B., 2024. Chapter 4 - goat farming: A boon for economic upliftment. In: Rana, T. (Ed.), *Trends in Clinical Diseases, Production and Management of Goats*. Academic Press, pp. 51–62. <https://doi.org/10.1016/B978-0-443-23696-9.00004-3>.
- Montcho, M., Assani, A.S., De Dieu Ainamon, J., Aboh, A.B., Olounladé, P.A., Sinsin, B., 2025. Agroecological mapping of livestock feed resources for sustain productivity and climate resilience in Benin (West Africa). *Discov. Sustain.* 6, 33. <https://doi.org/10.1007/s43621-024-00724-2>.
- Morand-Fehr, P., Fedele, V., Decandia, M., Le Frixoux, Y., 2007. Influence of farming and feeding systems on composition and quality of goat and sheep milk. *Small Rumin. Res.* 68, 20–34. <https://doi.org/10.1016/j.smallrumres.2006.09.019>.
- Nahed Toral, J., López Tecpoyotl, Z.G., Aguilar Jiménez, J.R., Grande Cano, D., Delgadillo Puga, C., 2021. Compliance of goat farming under extensive grazing with the organic standards and its contribution to sustainability in Puebla, Mexico. *Sustainability* 13, 6293. <https://doi.org/10.3390/su1316293>.
- Nampanzira, D.K., Kabasa, J.D., Nalule, S.A., Nakalembe, I., Tabuti, J.R.S., 2015. Characterization of the goat feeding system among rural small holder farmers in the semi-arid regions of Uganda. *SpringerPlus* 4, 188. <https://doi.org/10.1186/s40064-015-0961-3>.
- Palomino Guerrero, W., Godoy Padilla, D., Huaripaucar Huancahuari, J., Sessarego Dávila, E., Trillo Zárate, F., Cruz Luis, J., 2024. Characterization and typification of small-scale goat production systems in the highlands of southeast Peru. *Pastor. res. policy pract.* 14, 13035. <https://doi.org/10.3389/past.2024.13035>.
- Pardo, G., Martín-García, I., Arco, A., Yañez-Ruiz, D.R., Moral, R., Del Prado, A., 2016. Greenhouse-gas mitigation potential of agro-industrial by-products in the diet of dairy goats in Spain: a life-cycle perspective. *Anim. Prod. Sci.* 56, 646–654. <https://doi.org/10.1071/AN15620>.
- Paredes Chocce, M.E., Ramírez-Vergara, R., Trillo-Zárate, F.T., Cruz Luis, J., 2024. Characterization of dairy goat production systems in coastal valleys of the Lima region. *Trop. Anim. Health Prod.* 56, 1–12. <https://doi.org/10.1007/s11250-024-04143-3>.
- Patra, A.K., 2017. Accounting methane and nitrous oxide emissions, and carbon footprints of livestock food products in different states of India. *J. Clean. Prod.* 162, 678–686. <https://doi.org/10.1016/j.jclepro.2017.06.096>.
- Patra, A.K., Saxena, J., 2011. Exploitation of dietary tannins to improve rumen metabolism and ruminant nutrition. *J. Sci. Food Agric.* 91, 24–37. <https://doi.org/10.1002/jsfa.4152>.
- R Core Team, 2024. *R: A Language and Environment for Statistical Computing*.
- Ravhuhali, K.E., Msiza, N.H., Mudau, H.S., 2022. Seasonal dynamics on nutritive value, chemical estimates and in vitro dry matter degradability of some woody species found in rangelands of South Africa. *Agrofor. Syst.* 96, 23–33. <https://doi.org/10.1007/s10457-021-00683-x>.
- Robertson, K., Symes, W., Garnham, M., 2015. Carbon footprint of dairy goat milk production in New Zealand. *J. Dairy Sci.* 98, 4279–4293. <https://doi.org/10.3168/jds.2014-9104>.
- Ruiz-Llontop, D., Portocarrero-Villegas, S.M., Frias, H., Murga, L., Mantilla-Oliva, J., Pizarro, D.M., Velarde-Guillén, J., Saucedo-Urriarte, J.A., 2025. Greenhouse gas emissions from Fleckvieh cattle production systems in the Amazon region, Peru. *Trop. Anim. Health Prod.* 57, 83. <https://doi.org/10.1007/s11250-025-04358-y>.
- Salami, S.A., Luciano, G., O'Grady, M.N., Biondi, L., Newbold, C.J., Kerry, J.P., Priolo, A., 2019. Sustainability of feeding plant by-products: a review of the implications for ruminant meat production. *Anim. Feed Sci. Technol.* 251, 37–55. <https://doi.org/10.1016/j.anifeedsci.2019.02.006>.
- Sañudo, C., 2009. *Valoración morfológica de los animales domésticos*. Ministerio de Medio Ambiente y Medio Rural y Marino, Centro de Publicaciones, Madrid.
- Seidavi, A., Tavakoli, M., Rasouli, B., Corazzin, M., Salem, A.Z.M., 2020. Application of some trees/shrubs in ruminant feeding: a review. *Agrofor. Syst.* 94, 1353–1364. <https://doi.org/10.1007/s10457-018-0313-8>.
- SENAMHI, 2021. *Climas del Perú – Mapa de clasificación climática nacional*.
- Sessarego, E.A., Trillo, F.C., Godoy, D.J., Palomino-Guerrera, W., Cruz, J.A., 2025. Characterization and typology of goat production systems in the Southern Highlands of Peru. *Vet. World* 18, 220–227. <https://doi.org/10.14202/vetworld.2025.220-227>.
- Shah, A.M., Zhang, H., Shahid, M., Ghazal, H., Shah, A.R., Niaz, M., Naz, T., Ghimire, K., Goswami, N., Shi, W., Xia, D., Zhao, H., 2025. The vital roles of agricultural crop residues and agro-industrial by-products to support sustainable livestock productivity in subtropical regions. *Animals* 15, 1184. <https://doi.org/10.3390/ani15081184>.

- SIEA-MINAGRI, 2025. Producción pecuaria: Perfil productivo y competitivo de las principales especies y productos pecuarios. https://siea.midagri.gob.pe/siea_bi/.
- Sifuentes, R.C., Castillo, J.A., Peralta, H.G., Cochachin, E., 2014. Plantas silvestres empleadas como alimento para animales en Pisha, Ancash. *Ecología Aplicada* 13, 153–168.
- Teague, W.R., Apfelbaum, S., Lal, R., Kreuter, U.P., Rowntree, J., Davies, C.A., Conser, R., Rasmussen, M., Hatfield, J., Wang, T., Wang, F., Byck, P., 2016. The role of ruminants in reducing agriculture's carbon footprint in North America. *J. Soil Water Conserv.* 71, 156–164. <https://doi.org/10.2489/jswc.71.2.156>.
- Tilley, J.M.A., Terry, R.A., 1963. A two-stage technique for the *in vitro* digestion of forage crops. *Grass Forage Sci.* 18, 104–111. <https://doi.org/10.1111/j.1365-2494.1963.tb00335.x>.
- United Nations, 1992. Convención marco de las Naciones Unidas sobre el cambio climático. FCCC/INFORMAL/84.
- Zucali, M., Lovarelli, D., Celozzi, S., Bacenetti, J., Sandrucci, A., Bava, L., 2020. Management options to reduce the environmental impact of dairy goat milk production. *Livest. Sci.* 231, 103888. <https://doi.org/10.1016/j.livsci.2019.103888>.