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ACCOUNTING FOR BIOLOGICAL VARIABILITY IN ENTERIC METHANE EMISSIONS: IMPLICATIONS FOR LIFE CYCLE ASSESSMENT OF BEEF CATTLE SYSTEMS

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•**Abstract**: *Climate-related outcomes reported in life cycle assessment (LCA) studies of beef cattle systems often vary across production settings and methodological approaches, particularly in relation to the estimation of enteric methane emissions. Enteric methane constitutes a substantial portion of the greenhouse gas emissions profile in beef production systems; therefore, variation in enteric methane emissions is important for the interpretation of environmental assessment results. These differences arise from ruminal fermentation processes influenced by microbial activity, hydrogen metabolism, feed characteristics, and the combined effects of diet, animal-specific factors, and management practices. This review critically evaluates the microbial and other fermentation related determinants of enteric methane production in beef cattle systems and assesses their implications for LCA. It synthesizes current understanding of the biological mechanisms underlying enteric methane production, the impact of feed composition and fermentation dynamics, and the extent to which biologically driven variability in methane emission is incorporated into LCA studies. The review further identifies methodological challenges that hinder comparability across studies, such as inconsistencies in methane estimation techniques, functional units, system boundaries, and reporting standards. By connecting rumen microbial processes with system-level environmental assessment, this review offers a more integrated framework for interpreting LCA results in beef cattle systems and outlines priorities for future evaluations that are both biologically informed and methodologically transparent.*

• Introduction

Enteric fermentation from farmed ruminants has been reported to account for approximately one quarter of anthropogenic methane (CH_4) emissions. In beef cattle LCA, enteric CH_4 is a major inventory flow contributing to climate-change impacts.

Life cycle assessment (LCA) is an established framework for evaluating beef cattle systems, but reported results depend on functional unit, system boundary, allocation procedure and the method used to estimate enteric CH_4.

This review links rumen-level biological mechanisms with system-level environmental assessment to support a transparent and biologically informed interpretation of beef cattle LCA results.

• Material and method

A review of biological and methodological factors influencing the representation of enteric CH_4 in beef LCA studies was conducted.

Targeted literature searches combined thematic blocks on beef cattle, rumen fermentation, CH_4 measurement and LCA methodology. Methodological guidance was also considered, including ISO 14040/14044, FAO LEAP guidelines and IPCC guidance.

Thematic synthesis was organised around five areas: biology of methanogenesis; dietary, animal and microbial sources of variability; measurement and modelling of CH_4; LCA methodological choices; and comparability, uncertainty and mitigation.

• Results and discussions

Biological basis

CH_4 is produced mainly by methanogenic archaea, primarily through hydrogenotrophic methanogenesis. Depending on diet and intake, CH_4 represents a loss of gross energy and reflects the way hydrogen is disposed of in the rumen.

The rumen microbiome contributes to between-animal variability that is not always visible when average emission factors are used.

Dietary drivers

Dry matter intake is a key predictor of total daily CH_4 production. Among dietary components, NDF concentration is positively related to CH_4 yield, while starch and starch:NDF ratio are negatively related; crude protein shows little relationship.

Animal-level variability

CH_4 phenotypes show measurable genetic components, but estimates depend on measurement method and should be interpreted together with productivity and robustness traits.

Measurement

Respiration chambers, SF_6 tracer and GreenFeed each have distinct strengths and limitations in precision, throughput and representativeness; comparability depends on transparent protocol reporting.

Inventory modelling

Tier 1 default factors do not explicitly represent much biological variability. Tier 2 uses gross energy intake and Ym, while Tier 3 or mechanistic models can reflect diet- and system-specific data when adequately parameterised.

LCA practice

Berton et al. reviewed 239 European cattle LCA studies from 2010–2024 and reported that 94% used attributional LCA and most used one product-based functional unit; product- and land-based indicators may lead to different interpretations.

Cusack et al. synthesised 292 paired beef-LCA comparisons and reported a 46% net GHG reduction with carbon-sequestration management and 8% with efficiency strategies; net-zero outcomes were reached in only 2% of studies.

Implications

Variability among beef LCA results may reflect both biological differences and methodological choices, particularly the way enteric CH_4 is measured, estimated and incorporated into the inventory.

• Conclusions

Enteric CH_4 emissions in beef cattle reflect a biologically variable inventory flow shaped by diet, intake, microbial activity, animal traits and management.

The methodological choice of Tier 1 versus Tier 2/3, functional unit, system boundary and allocation substantially affects whether LCA outputs reflect biological variability or category averages.

A biologically informed LCA framework should report diet and intake assumptions, CH_4 estimation method, uncertainty range and sensitivity of results to CH_4-related parameters.

Standardised measurement and reporting protocols are important for credible mitigation assessment, particularly when interventions act directly on rumen fermentation.

Table 1. Methods used to measure or estimate enteric CH_4 emissions and implications for LCA inventories

Method	Data generated / main use	Main limitation for LCA interpretation
Respiration chamber	Continuous individual gas exchange under controlled conditions; useful reference data	Low throughput and confinement may limit representativeness for grazing or commercial settings
SF_6 tracer technique	Individual animal estimates under grazing or field conditions	Requires tracer calibration, background correction and consistent multi-day sampling protocols
GreenFeed / spot sampling	Repeated short measurements during voluntary visits; useful for larger-scale phenotyping	Sensitive to visit pattern, visit duration and daily feeding cycle
IPCC Tier 1	Default emission factor by livestock category; practical for screening or national inventories	Biological variability is not explicitly represented
IPCC Tier 2 / Tier 3	Tier 2 uses GE intake × Y_m; Tier 3 can use detailed national or mechanistic models	Requires representative intake, Y_m, calibration data and uncertainty reporting

Table 2. Key methodological dimensions in life cycle assessment of beef cattle systems and their implications for CH_4 variability

LCA dimension	Options commonly applied	Implication for CH_4 variability
Emission factor tier	Tier 1; Tier 2; Tier 3 or mechanistic models	Determines whether CH_4 is represented through category averages, intake/diet parameters or detailed modelling
Functional unit	Per kg LW; per kg CW; per kg edible protein; per hectare	Changes whether CH_4 is interpreted relative to product output, nutritional value or land occupation
System boundary	Farm gate; slaughter/processor gate; cradle-to-grave	Determines whether enteric CH_4 is assessed mainly as an on-farm emission or within a wider supply-chain context
Mitigation scenario	Dietary additives; feeding management; genetic or microbiome-based options	Requires assumptions on delivery, persistence, productivity effects and additional upstream inputs
Uncertainty treatment	Parameter ranges; Monte Carlo; scenario or sensitivity testing	Shows whether conclusions depend on CH_4 yield, Y_m, intake or animal-performance assumptions

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