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ESTIMATES OF METHANE EMISSIONS FROM DAIRY CATTLE BASED ON MANURE MANAGEMENT SYSTEMS

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Abstract

This paper aimed to estimate methane (CH_4) emissions from manure produced by dairy cattle in Romania between 2016 and 2025. Data on the dairy cattle population were obtained from the National Institute of Statistics, while manure-related greenhouse gas (GHG) emissions were estimated using Tier 2 methodologies provided by the International Panel on Climate Change Guidelines (IPCC, 2019). Gross energy intake (GE), digestible energy (DE), and volatile solid excretion (VS) were calculated using national reference values, while the methane-producing capacity (B_0) and methane conversion factors (MCF) were based on IPPC (2019) default values. At the national level, methane emissions from dairy cattle manure decreased from 6.618 Gg CH_4 yr^{-1} (165.455 t CO_2-eq) in 2016 to 6.054 Gg CH_4 yr^{-1} (151.350 t CO_2-eq) in 2025. These results indicate a gradual reduction in methane emissions, mainly driven by the decline in dairy cattle numbers, and highlight the importance of accurate country-specific data for improving greenhouse gas inventories and supporting effective mitigation strategies in the dairy sector.

Key words*: dairy cattle, manure management, methane emissions.*

INTRODUCTION

Methane (CH_4) is a potent greenhouse gas, with a global warming potential (GWP) of 28–34 times higher that of carbon dioxide over a 100-year time frame (Forster et al., 2021; Manono, 2026). Its atmospheric concentration has more than doubled since pre-industrial times, largely driven by anthropogenic activities, with livestock production identified as one of the principal global sources (Skeie et al., 2023).

Worldwide, livestock systems constitute a major source of anthropogenic methane (Nugrahaeningtyas et al., 2024; Xie et al., 2025), mainly through enteric fermentation and manure handling (Popa et al., 2025).

Usually, practices of manure management strongly influence methane emissions, as anaerobic decomposition of volatile solids in stored manure can lead to substantial CH_4 production (IPCC, 2006; IPCC, 2019). The magnitude of these emissions depends on factors such as manure storage type, temperature, retention time, and the biochemical characteristics of the manure itself (Im et al., 2020; Cheng et al., 2022).

Manure composition is influenced by the type of animal (beef or dairy), production stage, production type, and type of feeding (Symeon et al., 2025). Accurate estimation of methane emissions from manure is therefore essential for national greenhouse gas inventories and guiding the development of effective mitigation strategies within the livestock sector. In the livestock sector, dairy cattle represent a significant emission source due to their high feed intake, intensive production systems, and the large quantities of manure they generate (Stolarski et al., 2025).

In the European Union, agriculture accounts for about 54% of total methane emissions, with dairy cattle responsible for about 42% through enteric fermentation and 8% from manure production. Enhancing the precision of emission estimates has therefore become a central priority under the EU's 2050 climate-neutrality objectives (EEA, 2022).

Given these considerations, updated and accurate estimates of methane emissions from dairy cattle manure are essential for Romania's climate reporting obligations and for identifying mitigation opportunities in the dairy sector.

By integrating national data on cattle populations with refined calculations of gross energy intake, digestible energy, and volatile solid excretion, this study improves emission estimates and highlights trends relevant to

policy development and sustainable livestock management.
In this context, the present study aims to quantify CH_4 emissions from the dairy cattle sector in Romania, with a focus on manure handling and management systems.

MATERIALS AND METHODS

The dairy cattle population used in this paper to estimate CH_4 emissions was reported by the National Institute of Statistics (INS, 2025).
For accuracy, methane (CH_4) emissions from manure were calculated for an experimental Romanian Black and Spotted dairy cattle herd at the Research and Development Institute for Bovine Balotesti during the 2022-2025 period.
Methane emissions from manure handling and management systems were estimated using the Tier 2 methodology, following the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006; IPCC, 2019), and applying the corresponding equations:

CH_4 emissions from manure management (10.22)

$$CH_{4\ Manure} = \sum_{(T)}\left[\left(EF_{(T)} * N_{(T)}\right)/10^6\right]$$

where:
Emissions = methane emissions from enteric fermentation, Gg CH_4/yr^{-1};
$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4 /$head^{-1}/yr^{-1}$;
$N_{(T)}$ = the number of head of livestock species/category T in the country;
T = species/category of livestock.

CH_4 emission factor from manure management (10.23)

$$EF_{(T)} = (VS_T * 365) * \left[B_{0(T)} * 0.67 * \sum_{S,k}(MCF_{S,k}/100) * AWMS_{(T,S,k)}\right]$$

where:
$EF_{(T)}$ = annual CH_4 emission factor for livestock category T, kg CH_4 /$animal^{-1}/year^{-1}$;
$VS_{(T)}$ = daily volatile solid excreted for livestock category T, kg dry matter/$animal^{-1}/day^{-1}$;
365 = basis for calculating annual VS production, $days/year^{-1}$;
$B_{0(T)}$ = maximum methane producing capacity for manure produced by livestock category T, m^3 CH_4/kg^{-1} of VS excreted;
0.67 = conversion factor of m^3 CH_4 to kilograms CH_4;
$MCF_{(S,k)}$ = methane conversion factors for each manure management system S by climate region k, percent;
$AWMS_{(M,S,k)}$ = fraction of livestock category T's manure handled using animal waste manure management system S in climate region k, dimensionless.

Volatile solid excretion rates (10.24)

$$VS = \left[GE * (1 - DE/100) + (UE * GE)\right] * \left[(1 - ASH)/18.45\right]$$

where:
VS = volatile solid excretion per day on a dry-organic matter basis, kg VS/day^{-1};
GE = gross energy intake, MJ /day^{-1};
DE% = digestibility of the feed in percent (e.g. 60%);
(UE∗GE) = urinary energy expressed as fraction of GE. Typically, 0.04 GE was considered urinary energy excretion by ruminants (reduced to 0.02 for ruminants fed with 85 percent or more grain in the diet);
ASH = the ash content of feed calculated as a fraction of the dry matter feed intake (0.08 for cattle);
18.45 = conversion factor for dietary GE per kg of dry matter (MJ kg^{-1}).
The manure emissions were expressed as Gg CH_4 /yr^{-1} and t CO_2-eq.
The animal waste manure management system (AWMS) was a solid storage.
The specific values for GE, DE, VS, and EF were obtained either from recently published research articles (Enculescu et al., 2025) or calculated directly in this study (Table 1).
The parameters B_0 (0.24 m^3 CH_4/kg VS), MCF (2 %), ASH (8%) and AWMS (1) were adopted from the default values recommended by the IPCC (2006; 2019).
UE∗GE was calculated by multiplying the urinary energy coefficient (0.04 for ruminants), expressed as a fraction of gross energy, with the gross energy intake (GE).

The gross energy intake (GE) was calculated based on the following equation:

GE (kcal/kg) = 5.72 ∗ GP + 9.5 ∗ GB + 4.79 ∗ CelB + 4.17 ∗ SEN (Stoica, 1997)

where:
GE = gross energy intake;
GP = crude protein;
GB = crude fat;
CelB = crude fibres;
SEN = non-nitrate extractable substances.
The percentage of digestible energy (DE) of raw energy was calculated according to the following relation:

DE % = (DE/GE) ∗ 100

Emission factor (EF) of 5.51 kg/head/year was considered for dairy cows with an average body weight of 650 kg, average milk yield of 15.00 kg/head/day and a diet (kg/head/day) consisting of 25-30 kg silage maize, 5 kg alfalfa hay, and 6 kg concentrates. Emission factors (EF) of 6.20 kg/head/year, 6.61 kg/head/year, 6.80 kg/head/year, and 6.90 kg/head/year were considered for dairy cows with an average body weight of 650 kg, average milk yield between 16.30-16.55 kg/head/day and a diet (kg/head/day) consists of 28 kg silage maize, 7 kg alfalfa hay, and 6 kg concentrates.
To quantify methane emissions (t CO_2-eq) from dairy cattle manure, the basic formula of the IPPC Tier 2 approach was applied:

$$Emissions = N_{(T)} * (EF_{manure}/1000) * GWP_{CH4}$$

where:
Emissions = methane emissions from manure management of dairy cattle, t CO_2-eq;
$N_{(T)}$ = the number of head of livestock species/category T in the country;
$EF_{(T)}$ = emission factor for the defined livestock population, kg $CH_4/head^{-1}/yr^{-1}$;
$GWP_{100\ CH4}$ = the global warming potential of CH_4 in 100 years;
1 kg CH_4= 25 kg CO_2-eq (Forster et al., 2007).

Table 1. The values used for calculations of methane emission from dairy cows' manure management systems

	GE[1], MJ/head/day	DE[2], MJ/head/day	DE, %	ASH[3], %	VS[4], kg dry matter/ head/day	EF[5], kg CH_4/head/ yr^{-1}	Source
The value used for the number of dairy cattle from Romania							
2016-2025	282.85	200.12	70.75	8	4.69	5.51	Enculescu et al., 2025
The value used for the number of dairy cattle from the Research and Development Institute for Bovine Balotesti							
2022	310.27	217.00	69.93	8	5.28	6.20	Enculescu et al., 2025
2023	312.34	211.93	67.85	8	5.63	6.61	Enculescu et al., 2025
2024	314.20	210.44	66.97	8	5.80	6.80	Enculescu et al., 2025
2025	329.00	223.30	67.87	8	5.9	6.93	Own calculation

[1]GE=gross energy intake; [2]DE=digestible energy; [3]ASH=ash content; [4]VS=volatile solid excretion; [5]EF = emission factor.

RESULTS AND DISCUSSIONS

Table 1 summarises the values used to estimate methane emissions from manure management systems in dairy cattle. For the national dairy herd (2016-2025), GE averaged 282.85 MJ head/day, with a corresponding VS output of 4.69 kg/head/day and an EF of 5.51 kg CH_4/head/year. In contrast, the Romanian and Black Spotted dairy cattle reference herd showed higher GE intakes (310-329 MJ head/day) and greater VS excretion rates (5.28-5.90 kg head/day), which consequently led to increased emission factors (6.20-6.93 kg CH_4/head/year). These differences reflect variations in feeding intensity, productivity, and management practices between herds. The evolution of methane emissions from the Romanian dairy cattle sector over the 2016-2025 period is presented in Table 2.
The number of dairy cows shows a continuous decline from 1.201.132 head in 2016 to 1.077.589 head in 2023, followed by a slight recovery in the 2024-2025 period.
This reduction in the national herd size directly drives the downward trend in total methane emissions, which decrease from 6.618 Gg CH_4/year in 2016 to 5.938 Gg CH_4/year in 2023, representing an overall reduction of approximately 10%. CO_2-equivalent emissions show a similar downward trend, decreasing from 165.455 t CO_2-eq to 148.450 t CO_2-eq over

the same period. The modest increase in 2024-2025 reflects the slight rise in animal numbers during these years. The results indicate that methane emissions from the Romanian dairy sector have decreased substantially over the past decade.

This reduction is not due to changes in emission intensity, but rather to the progressive decline in the national dairy herd.

The slight rebound in 2024-2025 suggests a stabilisation of the sector, with proportional effects on methane output.

Table 2. Summary of methane emissions estimated from the Romanian dairy cattle sector between 2016 and 2025

Years/Specification	Dairy cows, heads/year	Tier 2	CH_4 emission/head/year	
			Gg[2] CH_4/yr^{-1}	*t CO_2-eq*[3]
2016	1.201.132		6.618	*165.455*
2017	1.168.975		6.441	161.025
2018	1.170.076		6.447	161.175
2019	1.147.399		6.322	158.050
2020	1.130.638	EF[1]: 5.51	6.230	155.750
2021	1.118.342		6.162	154.050
2022	1.104.215		6.084	152.100
2023	1.077.589		5.938	148.450
2024	1.079.600		5.949	148.725
2025	1.098.915		6.054	151.350

[1]EF = emission factor; [2]Gg CH_4/yr^{-1} = gigagrams CH_4/year; [3]t CO_2-eq = tonne CO_2 equivalent.

Table 3 summarises the methane emissions generated by the Romanian Black and Spotted dairy cows' reference herd during 2022-2025.

The emission factors (EF) applied to this herd range from 6.20 to 6.90 kg CH_4/head/year, values that are higher than the national Tier 2 EF of 5.51 kg CH_4/head/year used for the national Romanian dairy herd.

These higher EF values reflect the higher gross energy intake, higher volatile solids excretion, and slightly higher milk yields. The diet provided (28 kg maize silage, 7 kg alfalfa hay, and 6 kg concentrates) supports increased productivity and consequently increases the methane generation potential from manure.

Despite the higher emission factors, the absolute methane emissions remain extremely low, ranging from 0.527 to 0.555 Gg CH_4/year (13.175 t CO_2-eq-13.875 t CO_2-eq), due to the very small herd size (77-85 head).

Table 3. Summary of methane emissions estimated from the Romanian Black and Spotted dairy cows

Years/Specification	Dairy cows, heads/year	Tier 2	CH_4 emissions/head/year	
			Gg[2] CH_4/yr^{-1}	*t CO_2-eq*[3]
2022	85	EF:6.20	0.527	13.175
2023	84	EF:6.61	0.555	13.875
2024	80	EF:6.80	0.544	13.600
2025	77	EF:6.90	0.531	13.275

[1]EF = emission factor; [2]Gg CH_4/yr^{-1} = gigagrams CH_4/year; [3]t CO_2-eq = tonne CO_2 equivalent.

Overall, the results of the present study suggest that the dynamics of methane emissions in the Romanian dairy cattle sector are influenced primarily by herd evolution, with the reductions in animal numbers being the main driver of the decline in total emissions during the analysed period. The differences observed between the national herd and the Romanian Black and Spotted cows reference herd highlight the major role of energy intake, ration digestibility, and volatile solids excretion in determining emission factors. Popa et al. (2017) reported a decreasing trend in CH_4 emissions in a buffalo farm, driven both by herd size reduction and by the transition to an organic farming system that improved manure management practices.

These findings are relevant for the dairy sector, suggesting that management interventions can significantly contribute to emission reductions, complementing the effects of herd structure.

Furthermore, the study conducted by Popa et al. (2021) demonstrated that feeding strategies represent an essential tool for reducing methane and CO_2 equivalent emissions from manure management systems. Ration variants rich in green forage generated the lowest emissions,

whereas diets with higher proportions of concentrates resulted in increased emissions from both enteric fermentation and manure.

These results showed that ration digestibility, composition, and structural balance directly influence the methanogenic potential of manure, complementing international observations on the role of forage quality in shaping emission dynamics.

International literature supports this integrated perspective. Benchaar & Hassanat (2019) showed that higher digestibility of corn silage can increase manure-derived methane emissions due to greater volatile solids excretion and higher degradability, while Van Gastelen et al. (2023) demonstrated that certain dietary modifications can reduce enteric CH_4 without increasing manure methane.

Additionally, Hanafiah et al. (2021) highlighted the influence of animal age and manure type on methanogenic potential, emphasising the importance of biological characteristics and post-excretion management. Therefore, methane emission reduction cannot be attributed to a single factor, but rather results from the interaction among herd size, production level, ration composition and digestibility, volatile solids excretion, and manure management practices.

An effective mitigation strategy must integrate all these components, avoiding the transfer of emissions from one source to another and ensuring a coherent, sustainable approach tailored to the specific conditions of Romanian dairy farms.

However, several limitations should be acknowledged. Firstly, the current study relied on Tier 2 IPCC methodology, which, although robust, depends on assumed or default values for certain parameters (e.g., B_0, MCF) that may not fully capture farm-specific variability. Additionally, the analysis focuses primarily on herd size, feeding characteristics, and manure management, without incorporating broader system-level factors such as feed quality, climatic conditions, or long-term changes in genetic potential.

The limited availability of detailed farm-level data, particularly for smaller herds, may also constrain the precision of emission estimates.

Future research should integrate direct measurements of manure characteristics, longitudinal monitoring of feeding practices, and farm-specific emission coefficients to refine national inventories and support more targeted mitigation strategies. Incorporating such detailed information improves the accuracy of national greenhouse gas inventories and supports more effective mitigation strategies aligned with EU climate policies.

CONCLUSIONS

This study shows that methane emissions from dairy cattle manure handling systems in Romania have declined mainly due to reductions in herd size, while emission factors remained strongly influenced by feeding practices and production intensity. Applying the IPCC (2019) Tier 2 methodology improved the accuracy of national estimates and highlighted the importance of system-specific data for inventory refinement and for developing effective, sustainable manure management strategies.

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