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Regional patterns and cluster analysis of agricultural methane emissions in the EU-27 countries

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Abstract: Agricultural methane emissions strongly contribute to global greenhouse gas production. Under these circumstances, meeting international climate goals, including the Global Methane Pledge or the European Green Deal, requires developing targeted mitigation strategies. However, research using advanced clustering techniques in a multilevel context remains scarce and mostly limited to CO_2 emissions. This lack of time-series studies addressing regional variability hinders efforts to develop effective mitigation strategies. This study addresses three main research questions: (*i*) What are the main trends in agricultural methane emissions in the EU-27 countries from 2013 to 2022? (*ii*) How can the EU countries be classified based on agricultural methane emissions *per capita*? (*iii*) What is the impact of selected agricultural and economic indicators, including the number of live bovine animals and land use, on the clustering of methane emissions? Combining hierarchical and k-means clustering with trend analysis, this research integrates data from Eurostat and the World Bank, thereby classifying the EU-27 countries into four clusters based on their agricultural practices and methane emissions profiles. The results highlight distinct emission patterns across the EU-27 regions, with farming systems characterised by high stocking rates and intensive production generating the highest *per capita* emissions. By contrast, extensive systems with lower animal density exhibit reduced methane intensities. These findings underscore the need to devise effective, region-specific, data-driven policies and strategies for mitigating methane emissions.

Keywords: emissions mitigation; global methane pledge; global warming; greenhouse gas; livestock; trend analysis

Greenhouse gases (GHGs) cause global warming and climate change (Jain et al. 2015), particularly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Mohajan 2017). Methane stands out among GHGs for its relatively high short-term warming potential – over a 20-year period – and its effect, up to 84 times higher than that of CO_2 (Zhang et al. 2021; IPCC 2022). In 2021, global methane emis-

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sions reached approximately 570 million tonnes, 60% of which were derived from human activities (UNEP 2021; Malley et al. 2023). Although methane is produced by both natural sources, anthropogenic activities account for most methane emissions, especially agriculture (42%), energy production (36%) and waste management (18%) (European Commission 2023). As a result, global methane concentrations continue to rise (EEA 2023).

Agriculture is the largest contributor to methane emissions, mainly through cattle farming and manure management (FAO 2023), in addition to rice cultivation and crop residue burning (UNEP 2021). Cattle farming contributes to methane emissions primarily through enteric fermentation, which takes place in the digestive system of ruminants such as cows, sheep and goats. For example, a single cow can produce up to 500 litres of methane per day; this amount can vary depending on the factors such as diet, breed and breeding conditions, but in any event, enteric fermentation accounts for up to 32% of all anthropogenic methane emissions (Zhang et al. 2021; Kelly and Kebreab 2023). In turn, manure handling can contribute to nearly 10% of agricultural methane emissions (IPCC 2022; Malley et al. 2023). Globally, livestock production releases more than 100 million tonnes of methane into the atmosphere per year (UNEP 2021), and this value has been steadily increasing since 2010, according to FAO (2023).

In the European Union (EU), the agricultural sector is also the main source of methane emissions, with a 54% share in 2020 (European Union 2022). Through enteric fermentation (80%) and manure management (18%), cattle farming accounts for most agricultural methane emissions in the EU. EU agricultural methane emissions have been declining since 1990. For instance, while livestock production increased by 11% compared to 2005, methane emissions decreased by 4% (European Union 2022), albeit slightly increasing since 2015 (EEA 2023). Accordingly, the EU supports action to reduce methane emissions, especially because the temperature target of the Paris Agreement (Cain et al. 2021) cannot be met without reducing emissions. By 2030, a 30% reduction in methane emissions would reduce global average temperatures by 0.2%, according to the Food and Agriculture Organisation (FAO 2023).

With this target in mind, EU countries and the USA launched the Global Methane Pledge (CCAC 2024), a voluntary initiative to reduce global methane emissions, during the COP26 Climate Summit in Glasgow, in 2021 (UNEP 2021). More than 159 countries signed up to the initiative by 2025 (CCAC 2024), including most EU Member States. Implementing such environmental protection measures may not only reduce emissions but also increase the sustainability of agricultural systems and significantly reduce economic losses and deaths caused by climate change (UNEP 2021; World Bank 2023). However, in the Global Methane Pledge, methane reduction measures are written in broad strokes. Each country should base its action plans on its economy, emissions profile and national targets.

Technological measures could be implemented to reduce agricultural methane emissions by up to 30%, according to the UNEP (2021) report. Recent studies have highlighted the potential of antimethanogenic feed additives, particularly 3-nitrooxypropanol (3-NOP) and red seaweed (*Asparagopsis*), in reducing enteric methane emissions. Meta-analyses report 30–40% mitigation effects along with positive impacts on farm economics (Liu et al. 2025; Pupo et al. 2025). Methane has a relatively short lifetime in the atmosphere, so reducing agricultural methane emissions may be one of the most effective and immediate strategies to mitigate its impact on global warming (EEA 2023). But while some studies on agricultural methane emissions have been conducted, most research has either focused on CO_2 emissions or failed to address this topic in a multilevel context using advanced clustering techniques (Di Vita et al. 2024). Furthermore, the role of specific agricultural factors, such as land size and livestock intensity, remains underexplored, particularly within the EU policy framework.

The main goal of this study is to identify regional patterns and classify the EU-27 countries based on their agricultural methane emissions profiles using advanced cluster analysis techniques. By combining the time-series trend analysis with agricultural and economic indicators such as live bovine animals and land use, the study aims to support data-driven policymaking tailored to regional contexts within the EU. To address this gap, the present study explores three main questions concerning agricultural methane emissions in the EU: (*i*) What are the main trends in agricultural methane emissions in the EU countries from 2013 to 2022? (*ii*) How can the EU countries be classified based

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on agricultural methane emissions *per capita*? (*iii*) What is the impact of selected agricultural and economic indicators on the clustering of methane emissions in the EU? Our results highlight the need for wide-ranging, country-specific initiatives aimed at reducing methane emission in the EU considering regional differences and heterogeneity between member states. It is important to note that the aim of this article is not to offer or present specific strategies or measures for reducing methane production in agriculture. The key point is to identify differences between the EU-27 countries based on relative indicators relating to methane production.

MATERIAL AND METHODS

This study investigates agricultural methane emissions in the EU-27 countries using a comprehensive methodological framework combining hierarchical and k-means clustering with trend analysis. While similar analytical approaches have previously been employed to examine CO_2 or total greenhouse gas emissions (Kijewska and Bluszcz 2016; Harsanyi et al. 2021; Rybak et al. 2022), our study specifically applies this approach to agricultural methane emissions.

The analysis encompasses three timelines: a cross-sectional examination of methane emissions and related agricultural indicators for 2022 (cluster analysis), an examination of agricultural methane emissions in 2022 (k-means analysis) and a longitudinal assessment of agricultural methane emissions from 2013 to 2022 (trend analysis). The dataset integrates information from two reliable sources: Eurostat and the World Bank. Indicators were carefully selected based on their association with the methane emissions profiles of EU-27 countries, incorporating both direct emission metrics and agricultural and economic characteristics with a potential effect on emission patterns.

Tables 1 and 2 present an overview of all indicators, including their definitions and sources. These tables provide a detailed data framework under-

Table 1. Dataset used in the research article

Database	Description	Unit	Available	Indicators*
Eurostat	total EU population	persons	https://ec.europa.eu/eurostat/databrowser/view/demo_gind__custom_1110718/default/table	CH_4_per_capita
Eurostat	methane emissions in agriculture	thousand tonnes (CO_2 equivalent)	https://ec.europa.eu/eurostat/databrowser/view/env_air_gge__custom_14695780/default/table	CH_4_per_capita, Agri_CH_4_share
Eurostat	methane emissions by source sectors	thousand tonnes (CO_2 equivalent)	https://ec.europa.eu/eurostat/databrowser/view/env_air_gge__custom_14695780/default/table	Agri_CH_4_share
Eurostat	animal populations by NUTS 2 region	thousand heads (animals)	https://ec.europa.eu/eurostat/databrowser/view/agr_r_animal__custom_14449692/default/table	Live_Bovine_Animals
Eurostat	utilised agricultural area by categories	main area (1 000 ha)	https://ec.europa.eu/eurostat/databrowser/view/tag00025__custom_14762636/default/table	Livetock_density, Arable_land_share, Pasture_share, Permanent_crops_share
World Bank	employment in agriculture (% of total employment)	%	https://databank.worldbank.org/metadataglossary/world-development-indicators/series/SL.AGR.EMPL.ZS	Agri_GDP_per_worker
World Bank	labour force, total	persons	https://databank.worldbank.org/metadataglossary/world-development-indicators/series/SL.TLF.TOTL.IN	Agri_GDP_per_worker
World Bank	agriculture, forestry and fishing, value added	% of GDP	https://databank.worldbank.org/metadataglossary/world-development-indicators/series/NV.AGR.TOTL.ZS	Agri_GDP_per_worker

*This column displays the indicator calculated by authors

Source: The authors according to World Bank and Eurostat, 2025

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Table 2. Indicators of hierarchical cluster analysis for 2022

Indicator name	Abbreviation	Units	Description
Agricultural methane emissions *per capita*	CH4_per_capita	thousand tonnes CH_4-eq *per capita*	agricultural methane emissions *per capita* enable comparisons of emissions between countries
Share of agricultural CH_4 in total CH_4	Agri_CH_4_share	%	the share of agricultural methane emissions in total methane emissions by country highlights the importance of agricultural emissions
Live bovine animals per hectare	Live_Bovine_Animals	heads per hectare	the number of cattle per hectare of agricultural land indicates the intensity of cattle rearing
Agricultural GDP per worker	Agri_GDP_per_worker	USD per worker	the value of agricultural GDP per worker indicates labour productivity
Share of arable land in total agricultural area	Arable_land_share	%	the share of arable land in the total agricultural area indicates the extent to which agricultural activities focus on crop production
Share of permanent pastures in total agricultural area	Pasture_share	%	the share of pastures in total agricultural area enables to assess ruminant livestock production and methane emissions
Share of permanent crops in total agricultural area	Permanent_crops_share	%	the share of permanent crops in total agricultural area is a key indicator for assessing the focus on vineyards, orchards, etc.

Source: The authors, 2025

lying our analysis, ensuring the transparency and reproducibility of our research methodology:

Table 1 outlines the dataset used in this research, encompassing eight key indicators retrieved from two primary databases: Eurostat and the World Bank. Data on population statistics, total and agricultural methane emissions, animal populations and agricultural land use categories were extracted from the provided Eurostat database. Data on agricultural employment, labour force and agricultural value added were extracted from The World Bank database.

All indicators on the EU-27 member states were collected for 2022, except for population and methane emissions data used in the trend analysing from 2013–2022. Each indicator was expressed as a specific unit of measurement and accompanied by its direct source link. This dataset enabled us to analyse agricultural methane emissions in relation to various structural and economic indicators across the EU-27 countries.

The following sections present a detailed methodological framework, addressing each of the three research questions by a specific analytical method. The three complementary approaches, namely hierarchical and k-means cluster analysis and trend analysis were individually elaborated to provide a clear understanding of the study methodology.

1. What are the main trends in agricultural methane emissions in the EU-27 countries from 2013 to 2022?

Statistical modelling of CH_4 emission trends

Regression model for trend estimation. CO_2 emission trends were analysed using a simple linear regression model:

$$y_t = \beta_0 + \beta_1 t + \varepsilon_t \quad (1)$$

where:

y_t – CO_2 emissions at time *t*;
β_0 – intercept (baseline emissions);
β_1 – slope (trend over time);
ε_t – error term (random fluctuations in emissions).

Computation of slope **(β_1).** The slope of the regression line, β_1, was computed using the least squares method:

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$$\beta_1 = \frac{n\sum(ty_t) - \sum t \sum y_t}{n\sum t^2 - (\sum t)^2} \quad (2)$$

where:
β_1 – slope (trend over time);
n – number of years in the time series;
t – time;
y – CO_2 emissions.

Computation of intercept **(β_0).** The intercept, β_0, was calculated as follows:

$$\beta_0 = \frac{\sum y_t - \beta_1 \sum t}{n} \quad (3)$$

where:
y_t – CO_2 emissions at time t;
β_0 – intercept (baseline emissions);
n – number of years in the time series;
t – time.

This value indicates the estimated level of emissions at the beginning of the period.

Significance testing. To determine whether the trend was significant, the t-statistic was computed:

$$t = \frac{\beta_1}{SE(\beta_1)} \quad (4)$$

where:
t – time;
β_1 – slope (trend over time);
SE(β1) – standard error of the slope, given by:

$$SE(\beta_1) = \sqrt{\frac{\sum 1\left(y_t - \widehat{y_t}\right)^2}{(n-2)\sum(t-\bar{t})^2}} \quad (5)$$

where:
y_t – CO_2 emissions at time t;
t – time;
n – number of years in the time series.

The corresponding P-value was used to assess whether the trend was significant.

Goodness-of-fit **(R^2).** The coefficient of determination, R^2, measuring how well the regression model fits the data, was calculated using the following formula:

$$R^2 = 1 - \frac{\sum\left(y_t - \widehat{y_t}\right)^2}{\sum(y_t - \bar{y})^2} \quad (6)$$

where:
y_t – CO_2 emissions at time t.

The closer to 1 the value is, the better the fit will be, reflecting a model that explains most of the variation in emissions data.

2. How can the EU-27 countries be grouped based on agricultural methane emissions *per capita*?

Clustering the countries using k-means

Data standardisation. To ensure that all attributes were consistently scaled, the data were standardised using the following formula:

$$X_{scaled} = \frac{X - \mu}{\sigma} \quad (7)$$

where:
X – original value;
μ – mean of the attribute values;
σ – for the standard deviation of the attribute.

Distance metric. Differences between points and their respective centroids were minimised by applying the Euclidean distance:

$$d = \sum_{i=1}^{n}(x_i - c_i)^2 \quad (8)$$

where:
x_i – value of the point in a multidimensional space;
c_i – coordinates of the centroid.

Clustering. The data were classified into 4 clusters based on methane emissions and emissions *per capita* using the k-means algorithm. The number of clusters was set based on the selected analysis. The algorithm iteratively assigned points to the nearest centroid and updated their positions. This approach enabled the effective segmentation of the countries by environmental indicator.

3. What is the impact of selected agricultural and economic indicators on the clustering of methane emissions in the EU?

Hierarchical clustering of the EU-27 countries based on agricultural and economic indicators

To answer the third research question, hierarchical cluster analysis was performed to identify pat-

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terns and groupings among EU-27 based on their agricultural methane emissions and on related agricultural and economic indicators (such as land sizes, live bovine animals, methane emissions in agriculture, employment in agriculture and agricultural GDP per worker) for 2022, the most recent available data. The seven indicators included in the analysis were selected for their association with agricultural methane emissions. This method was chosen for its well-established application in recent environmental studies. The analysis followed a widely used multivariate statistical approach that systematically groups objects based on their similarity to identify underlying patterns or structures in datasets. This methodological approach progressively builds a hierarchy of clusters through an iterative process, as detailed below.

Hierarchical clustering: Mathematical formulation

Distance calculation. The Euclidean distance was calculated to assess the dissimilarity measure between observations. Given two observations *x* and *y*, the Euclidean distance is defined as follows:

$$d = \sum_{i=1}^{n} \left(x_i - c_i \right)^2 \qquad (9)$$

where:

$d(x,y)$ – distance between observations *x* and *y*;

x_i, y_i – values of the *i* indicator for the observations *x* and *y*;

c_i – coordinates of the centroid;

n – number of indicators.

For computational efficiency and consistency with Ward's method, we used the squared Euclidean distance, a common choice for environmental datasets.

Clustering method: Ward's linkage. The hierarchical clustering procedure using Ward's method minimises within-cluster variance while maximizing between-cluster variance. The Ward's linkage distance between two clusters *A* and *B* is computed as follows:

$$D(A,B) = \sqrt{\frac{2n_A n_B}{n_A + n_B}} \left| c_A - c_B \right| \qquad (10)$$

where:

n_A, n_B – number of observations in clusters *A* and *B*;

c_A, c_B – centroids of clusters *A* and *B*;

$|c_A - c_B|$ – Euclidean norm between the centroids.

Standardisation: Z-score transformation. To ensure the comparability of indicators with different scales and units of measurement, all data were standardised using the z-score transformation:

$$z = \frac{x - \mu}{\sigma} \qquad (11)$$

where:

z – standardised value;

x – original value;

μ – mean of the population;

σ – standard deviation of the population.

Standardisation eliminated the effect of different measurement units and scales, with all indicators equally contributing to the clustering process. The optimal number of clusters was determined based on the elbow criterion and structure of the dendrogram, which plots the within-cluster sum of squares against the number of clusters. Hierarchical cluster analysis was performed using SPSS Statistics v29.0 (IBM, USA). The dataset was complete with no missing values for any study indicator. The indicators and their sources are described in Table 2.

In the cluster analysis (Table 2), the indicators were selected for their association with agricultural methane emissions. CH_4_per_capita was chosen because this indicator reflects how intensive the agricultural production is in terms of agricultural methane emissions *per capita*, highlighting the countries whose agricultural sector is a major source of methane emissions relative to their population. Agri_CH_4_share indicates the share of agricultural methane emissions in the total methane emissions of a country. Live_Bovine_Animals reflects the density of live cattle per unit of agricultural land, with higher values indicating a higher number of heads per unit area and, therefore, more intensive livestock production, which leads to higher methane emissions. Agri_GDP_per_worker expresses agricultural labour productivity as the value of agricultural GDP (in USD) per agricultural worker, with high values indicating a productive agricultural sector, most likely thanks to high technological equipment and efficiency. Conversely, lower values indicate lower productivity associated with traditional farming methods or lower technological intensity. Arable_land_share, pasture_share and permanent_crop_share express the three types of agricultural land as a percentage of total agricultural area in each country, i.e., the relative

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size of each type of agricultural area as a proportion of the total area. A high share of arable land indicates the high crop production, while a high share of pasture reflects a focus on cattle farming, the two main agricultural methane producers. In turn, cattle farming is less prevalent in countries with a higher share of permanent crops, mainly grown in vineyards and orchards.

RESULTS

1. What are the main trends in agricultural methane emissions in the EU-27 countries from 2013 to 2022?

The trend analysis of EU-27 CH_4 emissions from 2013 to 2022 identified several countries with a significant (P-value < 0.001) increase in emissions, including the Czech Republic, Ireland, Spain, Cyprus, Hungary, Poland and Portugal. The highest rate of increase was recorded in Spain, with a slope of 370.23, followed by Ireland (242.69) and Poland (163.29). The coefficient of determination (R^2), which measures the strength of the trend, was particularly high in Spain (0.96), Czech Republic (0.88), Ireland (0.88), and Poland (0.89), indicating a strong and consistent upward trend in emissions. Accordingly, these countries face challenges in reducing CH_4 emissions and meeting climate goals, requiring targeted mitigation policies and sustainable energy strategies.

The increasing trends in Spain, Ireland and Poland are strongly associated with livestock intensification. In Ireland, the removal of milk quotas and export-driven dairy expansion led to rapid herd growth and higher emissions from enteric fermentation (Smith et al. 2021). Spain's rise reflects intensification of meat production and limited adoption of methane abatement technologies (Aguilera et al. 2021). Poland, after a long-term reduction in cattle numbers after 1990, saw a rebound linked to policy and economic shifts (Harsanyi et al. 2021). On the contrary, decreasing trends in countries like Germany, France and Lithuania are attributed to efficient manure management, technological progress and mitigation-oriented policy frameworks (Broucek 2014; Grossi et al. 2018). Such dynamics confirms that methane emissions are shaped by both agricultural structure and policy engagement (Table 3).

2. How can the EU-27 countries be grouped based on agricultural methane emissions *per capita*?

By k-means clustering, the EU-27 countries were grouped based on their agricultural methane emissions *per capita*, as described in the methods section. This approach enabled us to identify distinct emission patterns and outliers among the states, facilitating a deeper understanding of environmental performance across the region (Figure 1).

Using the clustering analysis, the EU-27 countries were divided into four clusters based on their agricultural methane emissions, with each cluster reflecting a unique emission pattern. Cluster 0 consisted of countries with moderate *per capita* emissions, including Denmark (1 201.84) and the Netherlands (747.49), along with Italy, Poland, and Romania, which showed relatively lower values. Cluster 1 isolated Ireland as an extreme outlier, with exceptionally high emissions *per capita* (3 235.14), primarily due to its livestock-intensive agricultural sector. Cluster 2 encompassed large economies with high total methane emissions but moderate *per capita* values, such as Germany (409.97), Spain (563.46), and France (606.85). Cluster 3 included countries with moderate-to-high *per capita* emissions, featuring Belgium (491.41), Estonia (596.43), and Austria (547.41). These findings highlight significant disparities in agricultural methane emissions across the EU and suggest the need for targeted mitigation policies tailored to the characteristics of each cluster, particularly for high-emitting countries, such as Ireland and Denmark (Table 4).

3. What is the impact of selected agricultural and economic indicators on the clustering of methane emissions in the EU?

The EU-27 countries were divided into four clusters by the hierarchical cluster analysis. Unlike previous studies which mostly used emission clustering (Kijewska and Bluszcz 2016; Harsanyi et al. 2021; Rybak et al. 2022), the optimal representation of the data in this paper was 4 clusters.

This choice reflects a balance between interpretability and differentiation of countries with distinct agricultural practices and methane emissions profiles. The four clusters encompassed the following countries:

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Table 3. CH_4 emission trends in the EU-27 countries (2013–2022)

Country	Slope (β_1)	Intercept (β_0)	*P*-value	*t*-statistic	R^2	Trend
Belgium	–17.84	41 856.3	0.03	–2.73	0.48	falling
Bulgaria	–7.32	16 959.74	0.19	–1.43	0.2	constant
Czech Republic	42.43	–81 700.5	0	7.69	0.88	rising
Denmark	–13.91	35 336.36	0.17	–1.5	0.22	constant
Germany	–345.89	734 125.5	0	–6.34	0.83	falling
Estonia	0.27	237.92	0.93	0.1	0.0	constant
Ireland	242.69	–473 873	0	7.7	0.88	rising
Greece	–23.97	53 455.01	0.1	–1.86	0.3	constant
Spain	370.23	–721 685	0	14.06	0.96	rising
France	–531.38	1 116 727	0	–6.29	0.83	falling
Croatia	–37.37	77 004.17	0	–11.94	0.95	falling
Italy	–44.37	110 805.3	0.05	–2.26	0.39	constant
Cyprus	10.62	–21 047.6	0	8.47	0.9	rising
Latvia	–0.51	2 090.68	0.78	–0.29	0.01	constant
Lithuania	–26.36	55 259.14	0	–5.28	0.78	falling
Luxembourg	3.46	–6 455.51	0.02	2.84	0.5	rising
Hungary	34.46	–66 587	0	6.87	0.86	rising
Malta	–0.03	98.27	0.75	–0.34	0.01	constant
Netherlands	–41.25	96 704.21	0.35	–0.98	0.11	constant
Austria	–13.47	32 146.9	0.04	–2.53	0.44	falling
Poland	163.29	–313 880	0	7.9	0.89	rising
Portugal	53.18	–102 418	0	7.63	0.88	rising
Romania	–84.44	180 382.4	0	–4.53	0.72	falling
Slovenia	1.82	–2 401.38	0.57	0.59	0.04	constant
Slovakia	–20.31	42 203.81	0	–11.36	0.94	falling
Finland	–14.28	31 556.04	0.03	–2.72	0.48	falling
Sweden	–8.46	20 717.14	0.01	–3.41	0.59	falling

This table summarises the linear trend analysis of CH_4 emissions in the EU-27 countries from 2013 to 2022. The slope indicates the rate of change in emissions, while the intercept represents the baseline level. The *P*-value determines the significance of the trend, and R^2 measures how well the model fits the data. The "Trend" column classifies emissions as rising, falling, or constant
Source: The authors, 2025

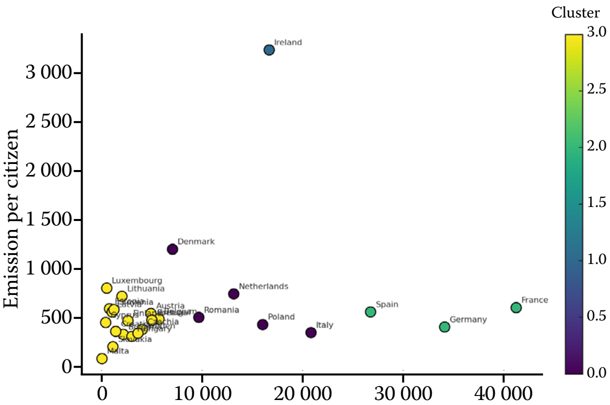

Figure 1. Clustering of the EU-27 countries based on agricultural methane emissions *per capita*
Source: The authors, 2025

- **Cluster 1:** Austria, Netherlands, Belgium, Luxembourg, Slovenia, Ireland;
- **Cluster 2:** Bulgaria, Romania, Croatia, Hungary, Poland, Latvia, Slovakia, Czech Republic, Malta;
- **Cluster 3:** France, Germany, Estonia, Lithuania, Sweden, Denmark, Finland;
- **Cluster 4:** Spain, Portugal, Italy, Greece, Cyprus.

Cluster 1. Austria, Netherlands, Belgium, Luxembourg, Slovenia, and Ireland. This cluster is characterised by exceptionally high livestock densities, typically exceeding 1.4 head per hectare (the Netherlands leads with 2 079 head/ha). These countries have the highest agricultural productiv-

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Table 4. Clustering of the EU-27 countries based on agricultural methane emissions *per capita*

EU country	Number of inhabitants	Methane emissions	Emissions *per capita*	Cluster
Denmark	5 873 420	7 058.94	1 201.84	
Italy	59 030 133	20 833.09	352.92	
Netherlands	17 590 672	13 148.8	747.49	0
Poland	36 889 761	16 025.15	434.41	
Romania	19 042 455	9 674.4	508.04	
Ireland	5 154 277	16 674.81	3 235.14	1
Germany	83 237 124	34 124.38	409.97	
Spain	47 486 843	26 756.78	563.46	2
France	67 957 053	41 239.78	606.85	
Belgium	11 617 623	5 709.06	491.41	
Bulgaria	6 482 484	2 170.22	334.78	
Czech Republic	10 516 707	4 055.84	385.66	
Estonia	1 331 796	794.33	596.43	
Greece	10 459 782	5 007.38	478.73	
Croatia	3 862 305	1 412.11	365.61	
Cyprus	904 705	412.23	455.65	
Latvia	1 875 757	1 055.49	562.7	
Lithuania	2 805 998	2 028.34	722.86	
Luxembourg	645 397	520.22	806.05	3
Hungary	9 610 403	3 015.82	313.81	
Malta	520 174	45.64	87.74	
Austria	8 978 929	4 915.14	547.41	
Portugal	10 421 117	5 000.97	479.89	
Slovenia	2 107 180	1 236.54	586.82	
Slovakia	5 434 712	1 129.7	207.87	
Finland	5 548 241	2 628.47	473.75	
Sweden	10 452 326	3 623.39	346.66	

Source: The authors, 2025

ity, with agricultural GDP per worker ranging from USD 50 000 to USD 91 517. The cluster encompasses countries with the highest methane emissions *per capita* (especially Ireland with 3 235 kg CH_4-eq) and with the highest share of agricultural methane in total methane emissions (64.5–80.6%). These countries boast highly developed agricultural systems with intensive livestock production, as evidenced by their high agricultural GDP and livestock density values. The proportion of permanent pasture is also significant (between 15% and 48%), as expected for intensive livestock systems.

Cluster 2. Bulgaria, Romania, Croatia, Hungary, Poland, Latvia, Slovakia, Czech Republic and Malta. These countries have significantly lower livestock densities (<0.3 head per hectare, with Bulgaria at 0.115 head/ha), agricultural productivity (USD 7 569–25 299 per worker), methane emissions *per capita* (334–547 kg CH_4-eq) and share of agricultural methane in total emissions (20.1–39.4%). The data show the predominance of arable land use (between 47% and 70% of total agricultural land) with limited livestock integration. The low values of agricultural GDP per worker and livestock density suggest less intensive farming practices. This cluster has the highest proportion of arable land, indicating that agricultural activities focus on crop production rather than on cattle farming.

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Cluster 3. France, Germany, Estonia, Lithuania, Sweden, Denmark and Finland. This cluster maintains moderate-to-high livestock densities (0.5–0.7 head per hectare) and significant agricultural productivity (USD 40 000–47 683 per worker). Methane emissions data show high *per capita* levels (600–1 201 kg CH_4-eq) and a significant share of agricultural methane in total emissions (65.6–80.6%). These countries display a balanced distribution of arable land (typically 55–65%) and permanent grassland (20–35%), indicating mixed farming systems. Their agricultural GDP per worker suggests advanced farming practices, while the livestock density indicates a more balanced approach compared to Cluster 1.

Cluster 4. Spain, Portugal, Italy, Greece and Cyprus. These countries have moderate livestock densities (average 0.4 head per hectare), agricultural productivity indicators (USD 15 811–37 045 per worker), moderate agricultural methane emissions *per capita* (352–563 kg CH_4-eq) and agricultural methane contributions (42.2–62.8%), with a significantly higher percentage of permanent crops (8–22% of agricultural land) and a lower proportion of permanent pasture than the Nordic countries, reflecting different land use patterns.

The results of the cluster analysis reveal distinct patterns of agricultural methane emissions affected by agricultural and economic indicators, as shown in the map below (Figure 2). High stocking densities and productivity account for increased emissions in Cluster 1, while extensive systems correlate with lower emissions profiles in Cluster 2. Cluster 3 reflects the complexity of diverse agricultural sys-

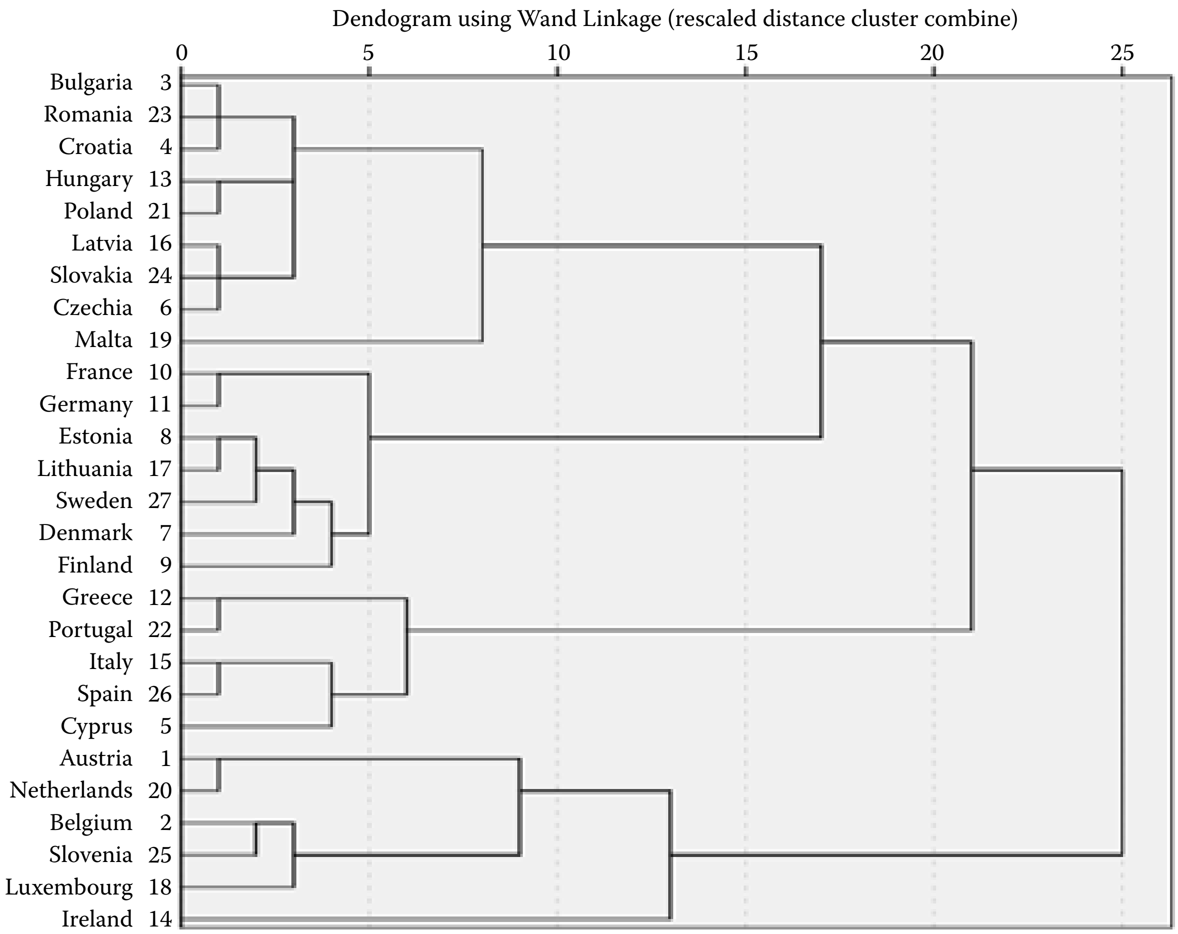

Figure 2. Dendrogram of the EU-27 countries generated using hierarchical clustering (Ward's method) based on agricultural methane emissions *per capita*, live bovine animals, and land use structure

The figure shows four distinct clusters representing different emissions profiles and structural agricultural patterns

Source: The authors, 2025

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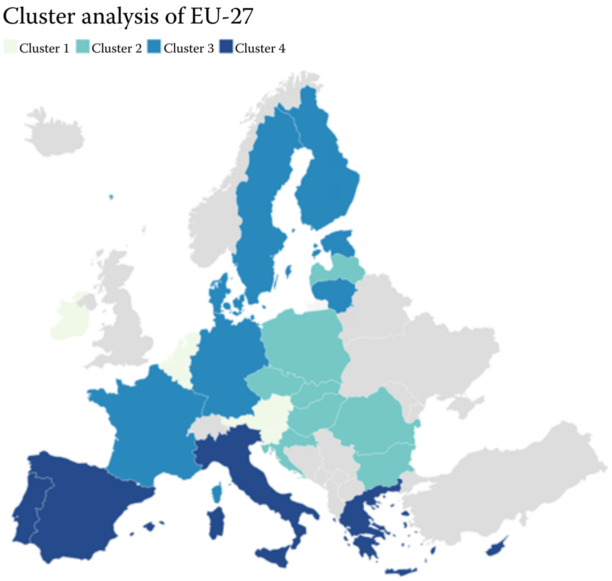

Figure 3. Visualisation of the cluster analysis of EU-27 agricultural methane emissions
Source: The authors, 2025

tems in which emissions derive from both livestock and crop farming. Cluster 4 underlines the role of climate and structural adaptations in shaping emissions. These findings highlight the need for mitigation strategies designed to address the specific agricultural characteristics of the countries in each cluster (Figure 3).

For better clarity of the results, a summary of the most important characteristics of the clusters according to the selected factors is available in Table 5.

DISCUSSION

Our multilevel analysis revealed different patterns of agricultural methane emissions and other factors across the EU countries. Agricultural methane emissions remain among the most significant climate policy challenges of the EU, accounting for approximately 44% of total methane emissions (Frank et al. 2019). Corroborating previous literature (De Cara and Jayet 2011), the heterogeneity of EU-27 agricultural methane emission patterns highlighted in this study showcases the need for differentiated approaches to methane mitigation strategies in EU agriculture rather than uniform measures to increase their effectiveness. For example, policy measures for Cluster 1 countries should optimise intensive agricultural systems while significantly reducing emissions. Cluster 2 countries could benefit from policies that support maintaining their relatively low emissions profiles while increasing agricultural productivity. Therefore, our findings provide key insights for achieving the goals of the Global Methane Pledge.

As shown by hierarchical cluster analysis, the EU-27 countries can be divided into four distinct groups based on their methane emissions profiles and other agricultural characteristics specifically related to these emissions. As such, this study extends previous research focused on clustering total GHG emissions in the EU (Kijewska and Bluszcz 2016; Rybak et al. 2022). The study by Harsanyi et al. (2021) analysed the agricultural sector, albeit

Table 5. Criteria and results of hierarchical cluster analysis for the year 2022

Classification criterion	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Countries	Austria, Netherlands, Belgium, Luxembourg, Slovenia, Ireland	Bulgaria, Romania, Croatia, Hungary, Poland, Latvia, Slovakia, Czech Republic, Malta	France, Germany, Estonia, Lithuania, Sweden, Denmark, Finland	Spain, Portugal, Italy, Greece, Cyprus
Livestock density	very high (<2 heads/ha)	low (<0.3 heads/ha)	moderate to high (0.5–0.7 heads/ha)	moderate (≈0.4 heads/ha)
Agricultural GDP per worker	highest (USD 50 000–91 527)	low (USD 7 569–25 299)	high (USD 40 000–47 683)	variable (USD 15 811–37 045)
Methane emissions *per capita*	very high (>3 000 kg CH_4-eq)	low (334–547 kg CH_4-eq)	high (600–1 201 kg CH_4-eq)	moderate (352–563 kg H_4-eq)
Share of agricultural CH_4	very high (64.5–80.6%)	low to moderate (20.1–39.4%)	high (65.6–80.6%)	moderate (42.2–62.8%)
Environmental impact	highest methane footprint	lower methane footprint	high methane footprint	moderate methane footprint

Source: The authors, 2025

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considering all GHGs. By contrast, this study is limited to one GHG and one sector, but it provides a new outlook of methane-specific emission factors and their regional distribution.

Our detailed analysis of the clusters revealed distinct characteristics consistent with previous research on EU agricultural emission patterns. Cluster 1 displays the highest *per capita* methane emissions, in line with, e.g., Brodny and Tutak (2021). The exceptionally high livestock density in these countries (>1.4 animals per hectare) and high agricultural productivity (USD 50 000–91 517 per worker) are consistent with studies linking agricultural intensity to increased methane emissions (Smith et al. 2021). The high share of agricultural methane in total emissions of this cluster (64.5–80.6%) matches patterns found by Broucek (2014) in regions with concentrated livestock production.

Cluster 2 shows how extensive agricultural practices can sustain lower emission intensities. Lower livestock density (<0.3 animals per hectare) and agricultural productivity (USD 7 569–25 299 per worker) lead to significantly lower methane emissions *per capita* (334–547 kg CH_4-eq.). According to Harsanyi et al. (2021), Hungary, Poland, Romania and the Czech Republic have decreased methane emissions. In Poland, this decrease was mainly due to an almost 50% reduction of livestock between 1990 and 2017 (Harsanyi et al. 2021) with the introduction of milk quotas in the EU. The predominance of arable land (47–70%) with the limited inclusion of livestock reflects traditional Eastern European agricultural patterns (Czyzewski and Michalowska 2022).

Cluster 3 encompasses countries with balanced farming systems that maintain moderate-to-high livestock densities (0.5–0.7 animals per hectare) and substantial agricultural productivity (USD 40 000–47 683 per worker). The emissions profile of this cluster corroborates research by Grossi et al. (2018) on optimised farming systems. For example, Germany showed a significant decrease in methane emissions between 1990 and 2021, while CH_4 emissions increased. In contrast, all agricultural emissions decreased in France over the same period, a country with a 25% share of livestock in Europe (Harsanyi et al. 2021). On average, countries in this cluster boast a balanced distribution between arable land (55–65%) and permanent grassland (20–35%), indicating an efficient use of agricultural land.

Cluster 4 shows countries with moderate livestock density (average 0.4 animals per hectare) and agricultural productivity indicators (USD 15 811–37 045 per worker). The average livestock density (0.4 animals per hectare) is consistent with the findings of Sanz-Cobena et al. (2017), who reported that the agriculture sector in Mediterranean countries results in low methane emissions. The high share of permanent crops (8–22% of agricultural land) supports the conclusions of Bernues et al. (2011) and Harsanyi et al. (2021) on the environmental impact of these countries in this cluster. The less intensive farming systems in these countries have lower absolute methane emissions and are efficient in terms of unit production per area (Aguilera et al. 2021).

The trend analysis of methane emissions over the period 2013–2022 revealed asymmetries among the EU-27 countries in their progress to reducing methane emissions. Some countries achieved significant reductions, while others showed only slight improvements or even increases in methane emissions. The EU as a whole has decreased methane emissions by 36% over the last 30 years compared to 1990 (EEA 2023), but as mentioned by Key and Tallard (2011), achieving significant reductions in methane emissions is essential to meet global climate goals. Therefore, developing countries must put more effort into applying mitigation strategies.

Several limitations of this study should be considered when interpreting the results. A longer time span than the period 2013–2022 could reveal long-term patterns and fluctuations. In addition, this study relied on secondary data retrieved from Eurostat and the World Bank, so differences in the precision of methane emissions measurements and seasonal variations may lead to inconsistencies in results when using other databases, as confirmed by Pison et al. (2018). Our cluster analysis included several factors, but the lack of data prevented us from fully accounting for all factors, such as specific soil conditions, climatic differences, and manure management practices. Future research should address policy strategies within each cluster (focusing on their regional specifications) and the economic implications of cluster-specific methane mitigation strategies.

CONCLUSION

This study provides a detailed exploration of the regional variability in agricultural methane emissions across the EU-27, offering a novel outlook

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of the interplay between emission intensities and agricultural structures. The trend analysis from 2013 to 2022 revealed that several countries, including Spain, Ireland, and Poland, experienced significantly increasing methane emissions, primarily due to livestock intensification and policy shifts, while others like Germany and France showed decreasing trends linked to effective mitigation strategies and technological progress. These findings directly address the first research question and demonstrate how emission trajectories differ between the Member States, reinforcing the importance of national policies and structural contexts in shaping the methane dynamics.

Cluster analysis divides the EU-27 countries into four clusters, each characterised by unique agricultural practices and emissions profiles. High-intensity systems produce the highest emissions *per capita*, while extensive systems display lower levels, underscoring diverse challenges for targeted mitigation efforts in the EU. These findings emphasise the importance of region-specific approaches to methane reduction balancing agricultural productivity with environmental sustainability. By aligning these strategies with broader EU climate goals, such as the Global Methane Pledge and the European Green Deal, policymakers may design effective and equitable interventions. This study advances the understanding of the methane emission dynamics and provides actionable insights to inform about such sustainable agricultural policies. By building on this framework, the EU may foster a more resilient agricultural sector, contributing to global climate targets while maintaining regional economic viability.

Conflict of interest

The authors declare no conflict of interest.

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