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ANALYSIS OF THE CARBON FOOTPRINT AT FARM GATE IN THE EUROPEAN UNION CONTEXT

ABSTRACT

This paper analyses the evolution of carbon footprint at farm gate level in the EU-27, in the period 2014–2023. The study is based on FAOSTAT emissions data processed according to the IPCC AR5 methodology, with all greenhouse gas emissions expressed in CO_2 equivalent (kt CO_2 eq). The research integrates emissions generated by crop production, livestock activities, and on-farm energy consumption. Methodologically, the analysis combines inventory-based approaches with descriptive and comparative statistical methods, including structural analysis and inter-period comparisons (2014–2018 *versus* 2019–2023). The results indicate that chemical fertilisers remain the dominant source of emissions in crop production, accounting for approximately 45–65% of total crop-related emissions, while enteric fermentation contributes around 63–66% of livestock emissions. The study highlights a significant decline in crop residue burning and a gradual transition towards more sustainable agricultural practices. In the energy sector, petroleum products became increasingly dominant, reflecting the persistence of fossil-fuel-dependent mechanisation. Comparative analysis across EU member states reveals considerable disparities in carbon footprint intensity, driven by differences in agricultural structure, technological development, and input use intensity. Germany, France, Poland, Spain, and Italy recorded the highest total emissions, while Romania showed a relatively stable but moderately declining trend after 2019. The findings suggest the existence of a partial decoupling between agricultural production growth and greenhouse gas emissions, largely influenced by the Common Agricultural Policy and the European Green Deal. However, this decoupling remains incomplete due to the structural dependence on nitrogen fertilisers and biological emissions from livestock. The paper emphasises the importance of precision agriculture, renewable energy integration, improved manure management, and carbon accounting systems at farm level. The study concludes that carbon footprint estimation is not only an analytical exercise but also a strategic instrument for designing climate-oriented agricultural policies capable of balancing productivity, food security, and environmental sustainability in the EU agricultural sector.

Key words: carbon footprint, EU-27, FAO methodology

JEL Classification: Q10, Q56

1. INTRODUCTION

Agriculture plays a strategic role in the economy of the European Union, ensuring food security, rural development, and the sustainable management of natural resources. At the same time, the agricultural sector represents one of the

major sources of greenhouse gas (GHG) emissions, contributing significantly to climate change through methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions generated by agricultural activities. In this context, the estimation of carbon footprint at farm gate level has become an essential instrument for evaluating the environmental performance of agricultural systems and for supporting climate-oriented public policies.

Over the last decades, increasing concerns regarding global warming and environmental degradation have intensified the need for accurate monitoring and reduction of agricultural emissions. International organisations such as the Intergovernmental Panel on Climate Change have developed standardised methodologies for estimating agricultural greenhouse gas emissions, allowing comparability between countries and production systems. In parallel, the European Union has integrated climate objectives into agricultural policies through the Common Agricultural Policy and the European Green Deal, aiming to achieve climate neutrality by 2050.

The evolution of agriculture in Central and Eastern Europe, particularly in Romania, reflects a complex process of structural transformation after 1990. The transition from a centrally planned economy to a market-oriented agricultural system generated significant changes in land use, livestock populations, technological intensity, and input consumption. These transformations strongly affected the dynamics of greenhouse gas emissions and the carbon footprint of agricultural farms.

In the first post-communist decade, agricultural emissions declined sharply due to the collapse of intensive production systems, reduction in livestock numbers, and decreased use of chemical fertilisers and fossil fuels. After the accession to the European Union, agricultural production gradually intensified, supported by modernisation processes, financial support mechanisms, and integration into European markets. As a result, the relationship between agricultural productivity and environmental impact became increasingly important in both scientific research and policy debates.

The current study emphasises that the agricultural carbon footprint is characterised by considerable heterogeneity across EU member states. Differences in climatic conditions, farm size distribution, technological adoption, and production specialisation generate significant disparities in emission levels and emission intensity. Large commercial farms generally benefit from higher technological efficiency, whereas small and medium-sized farms often face limitations related to capital access, innovation, and environmental management.

At methodological level, the estimation of the agricultural carbon footprint has evolved from aggregate national inventories towards farm-level assessments with higher spatial and temporal precision. In addition to IPCC inventory approaches, Life Cycle Assessment methodologies are increasingly used to evaluate emissions throughout the entire production chain. Moreover, digital technologies such as precision agriculture, satellite monitoring, sensors, and

artificial intelligence create new opportunities for real-time carbon monitoring and optimisation of agricultural inputs.

Despite these advances, important challenges remain regarding the availability and quality of farm-level data, especially in countries with dual agricultural structures such as Romania. The lack of detailed databases, regional emission coefficients, and integrated monitoring systems limits the accuracy of carbon footprint estimation and the effectiveness of climate policies.

Against this background, the present study aims to analyse the evolution of carbon footprint at farm gate level in the EU-27, in the period 2014–2023 period. The research is based on FAOSTAT emission data processed according to IPCC AR5 methodology and examines the contribution of crop production, livestock farming, and energy consumption to total agricultural emissions. Furthermore, the paper investigates structural changes in emission patterns, comparative differences between member states, and the implications of recent environmental policies for the transition towards sustainable and climate-resilient agriculture.

2. STATE OF KNOWLEDGE

The carbon footprint is an indicator that measures the total amount of greenhouse gas (GHG) emissions generated by an agricultural activity. It is expressed in carbon dioxide equivalent (CO_2eq), by converting methane (CH_4) and nitrous oxide (N_2O) emissions into CO_2 equivalents in order to ensure comparability between different greenhouse gases. In practical terms, the carbon footprint represents the cumulative impact of all greenhouse gases emitted during the production process. While greenhouse gases indicate the specific gases emitted (CO_2, CH_4, N_2O), the carbon footprint reflects the total volume of emissions expressed in standardised units (kt CO_2eq). Therefore, the carbon footprint can be defined as the accounting and quantification of total greenhouse gas emissions associated directly and indirectly with agricultural production activities.

In agriculture, the carbon footprint includes emissions resulting from crop production, livestock farming, manure management, fertiliser application, and energy consumption at farm level. These emissions are strongly influenced by the structure of agricultural production, the intensity of input use, technological development, and the implementation of sustainable farming practices.

The current state of knowledge regarding carbon footprint estimation at farm level lies at the intersection of international methodological progress, climate policy pressure, and the need to adapt analytical models to local agro-ecological conditions. Over recent decades, research in this field has evolved from aggregated national-scale assessments towards microeconomic and farm-centred approaches characterised by a higher degree of detail, precision, and policy relevance.

At conceptual level, there is broad scientific consensus regarding the main sources of agricultural emissions and the methodologies used for their quantification.

The methodologies developed under the framework of the Intergovernmental Panel on Climate Change constitute the global standard for greenhouse gas accounting. These methodologies provide stratified approaches (Tier 1–3), allowing progressively more accurate estimates depending on data availability and methodological complexity. In addition, these approaches are increasingly complemented by Life Cycle Assessment (LCA) methodologies, which extend the analysis beyond farm boundaries by incorporating indirect emissions associated with agricultural inputs, processing, and other stages of the agro-food chain.

Within the European Union, the research and policy framework has been strongly influenced by the European Commission through instruments such as the Common Agricultural Policy and the European Green Deal. These initiatives have stimulated the development of harmonised databases, including FAOSTAT, as well as regional estimation models that facilitate comparability among member states and support the monitoring of progress towards climate neutrality objectives.

The current state of knowledge is characterised by significant but uneven progress. Although robust macroeconomic estimates based on national emission inventories are available, farm-level analyses remain constrained by limited data availability and insufficient data granularity. Existing studies reveal substantial variability in carbon footprint intensity depending on farm typology, production systems, and the level of technological intensification. Furthermore, important challenges persist regarding the integration of indirect emissions and the quantification of agro-ecological processes such as soil carbon sequestration.

Nevertheless, the implementation of modern technologies (precision agriculture, satellite imagery, remote sensing technologies, and artificial intelligence that increasingly enable high-resolution and real-time estimations of carbon flows within agricultural systems) remains relatively limited, particularly on small and medium-sized farms, where financial and technological constraints continue to hinder adoption.

In conclusion, the current state of knowledge regarding carbon footprint estimation in agriculture is highly developed at theoretical and methodological level, yet still undergoing consolidation at the applied level, particularly in agricultural economies characterised by dual farm structures such as Romania. The discrepancy between modelling capacity and the availability of detailed empirical data remains one of the main challenges for the development of efficient environmental policies adapted to local agricultural realities.

3. MATERIAL AND METHOD

The present research is based on an integrated methodological framework specific to agricultural and environmental economics, aiming to estimate and analyse the dynamic evolution of the carbon footprint associated with agricultural farms in the period 2014–2023. The approach is quantitative in nature, combining

inventory-based and analytical methods founded on internationally recognised standards and globally harmonised databases.

The estimation of greenhouse gas (GHG) emissions was conducted in accordance with the guidelines developed by the Intergovernmental Panel on Climate Change, particularly those included in the Fifth Assessment Report (AR5, 2014). Within this framework, emissions are expressed in carbon dioxide equivalent (CO_2eq), using the Global Warming Potential (GWP) specific to each gas (CH_4 and N_2O), thus ensuring aggregation and comparability across categories and time periods.

The methodological approach complements the Life Cycle Assessment (LCA) perspective; however, the analysis is limited to the "on-farm" level, excluding downstream stages of the agri-food chain such as processing, transport, and distribution, with the exception of electrical and thermal energy produced off-farm, but consumed on the agricultural holding.

The data used in this study were extracted from the "Emissions" statistical domain of FAOSTAT, which provides coherent and comparable time series regarding agricultural greenhouse gas emissions, updated on 28 October 2025. The database structures emissions into three main categories at farm level: emissions from crop production; emissions from livestock production; and emissions resulting from energy consumption on the farm.

The study applies the AR5 methodology of the Intergovernmental Panel on Climate Change (2014), which includes emissions expressed in CO_2 equivalent (AR5), fluorinated gas emissions (AR5), CH_4 emissions converted into CO_2 equivalent (AR5), and N_2O emissions converted into CO_2 equivalent (AR5).

According to the FAOSTAT classification, the analysed emission sources are structured as follows:

- Crop emissions: This category includes biogeochemical processes specific to the crop sector, namely crop residues, burning of crop residues, rice cultivation, and the application of nitrogen fertilisers. These processes generate mainly N_2O emissions and, in certain cases (crop burning and rice cultivation), CH_4 emissions.
- Livestock emissions: This category reflects metabolic and manure management processes, including enteric fermentation (the major source of CH_4 emissions), manure application to soils, manure deposited directly on pastures, and manure management systems, which generate combined CH_4 and N_2O emissions.
- Emissions from on-farm energy consumption: This category includes emissions generated by the use of petroleum products, natural gas, electricity, thermal energy, and coal associated with agricultural activities such as mechanisation, irrigation, and heating, including energy produced outside the farm but consumed on the holding.

In order to ensure comparability, all emission categories were converted into CO_2 equivalent, allowing the determination of: total agricultural emissions; percentage structures by categories and subcategories; temporal dynamics of the carbon footprint.

The analysis is based on the agricultural carbon footprint at national level, expressed in kt CO_2eq. Methodologically, the study employs:

- time-series analysis (2014–2023);
- inter-period comparisons (2014–2018 *versus* 2019–2023);
- descriptive and interpretative methods specific to environmental economics.

Although the methodology used is robust and aligned with international standards, several limitations should be acknowledged:

- the use of average emission factors (Tier 1–2), which may underestimate local variability;
- the absence of detailed farm-level data;
- the exclusion of downstream agri-food chain emissions (including fluorinated gases);
- difficulties related to quantifying soil carbon sequestration processes.

The study focuses exclusively on emissions generated within the agricultural system of the European Union in the period 2014–2023, with all results expressed in CO_2 equivalent. This delimitation allows for a coherent analysis of carbon footprint evolution and provides a solid basis for the development of environmental policies aimed at the decarbonisation of agriculture.

4. RESULTS AND DISCUSSIONS

4.1. DYNAMICS OF THE CARBON FOOTPRINT AT FARM GATE, EU-27, 2014–2023

The European Union is estimated to have caused 10 percent of global warming since 1850 and is responsible for around 17 percent of historical global carbon dioxide emissions. Nevertheless, the EU has been a world leader in cutting emissions in recent decades. From 1990 to 2023, EU emissions of carbon dioxide (CO_2) fell by roughly 35%, while its GDP grew by more than 70 percent over the same period. The EU now has its sights set on becoming the world's first major economy to achieve climate-neutrality by 2050.

The following major trends by emission categories were observed in the period 2014–2023 period:

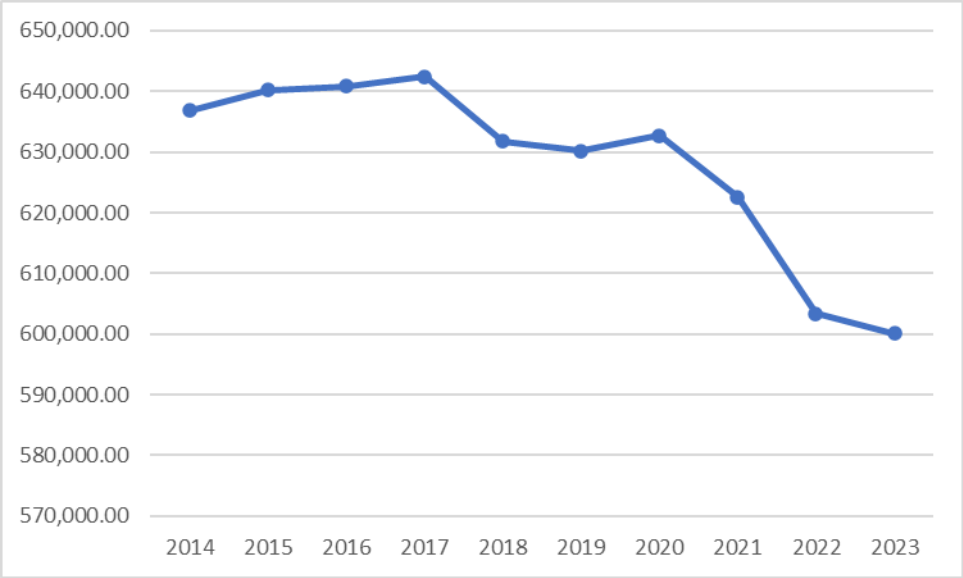
The evolution of the carbon footprint in the crop production sector highlights a direct relationship between agricultural intensification and the increase in greenhouse gas emissions, particularly through the use of chemical fertilisers. At

present, the main challenge lies in decoupling agricultural production growth from the rise in emissions by optimising fertiliser use, adopting precision agriculture, and implementing sustainable practices.

The evolution of carbon footprint in the livestock sector is predominantly driven by structural factors (herd size) rather than technological progress. In the recent period, active interventions are required, such as optimising animal nutrition, using methane reduction technologies, and recovering energy from manure.

The evolution of emissions from energy consumption in agriculture highlights a direct relationship between the level of technological development and the energy intensity of the sector.

In this context, the strategies promoted by the European Union through the European Green Deal become essential for the decarbonisation of energy consumption, the electrification of agricultural processes, and the integration of renewable energy sources into agricultural holdings.



Source: Data processed by the author, FAO, 2025.

Figure 1. Carbon footprint at farm gate in the European Union (EU-27).
for the period 2014–2023 (Kt CO_2eq).

In the agricultural sector, the period 2014–2023 was characterised by moderate but uneven reductions in farm gate carbon emissions across member states, influenced by structural reforms, technological modernisation, and the implementation of climate-related policies under the Common Agricultural Policy and the European Green Deal. The results reveal that emission reductions were mainly associated with improvements in resource efficiency, reduced crop residue burning, gradual modernisation of livestock management systems, and the adoption

of more sustainable agricultural practices (Figure 1). Nevertheless, important challenges persist due to the continued dependence on nitrogen fertilisers, fossil-fuel-based mechanisation, and biological emissions from enteric fermentation. Consequently, the analysed period illustrates both the progress achieved by the EU in reducing agricultural emissions and the structural limitations that continue to constrain the transition towards full climate neutrality by 2050.

4.2. DYNAMICS OF THE FARM-GATE CARBON FOOTPRINT IN THE EUROPEAN UNION MEMBER STATES IN THE PERIOD 2014–2023

At aggregate level, the highest cumulative emissions are observed in Germany (515,067.62 kt CO_2eq) and France (479,430.33 kt CO_2eq), followed by Poland (387,207.19 kt CO_2eq), Spain (256,125.33 kt CO_2eq), and Italy (221,929.42 kt CO_2eq). These Member States collectively dominate the EU agricultural emissions profile, largely due to their extensive agricultural land base, high livestock densities, and intensive input use systems, particularly nitrogen-based fertilisation and mechanised crop production. In contrast, significantly lower emission levels are recorded in smaller Member States such as Malta (584.03 kt CO_2eq), Luxembourg (3,826.34 kt CO_2eq), and Cyprus (3,055.30 kt CO_2eq), where structural constraints and limited agricultural area inherently restrict total emission volumes.

From a temporal perspective, most countries exhibit relatively stable interannual emission trajectories **in the period 2014–2018**, with minor fluctuations reflecting climatic variability, yield dynamics, and input use adjustments. Northern and Western European countries such as Finland, Sweden, and Denmark show consistent emission patterns, indicative of highly stabilised and technologically optimised agricultural systems. In contrast, Central and Eastern European countries, including Romania, Poland, and Hungary, display slightly increasing trends, consistent with gradual post-accession agricultural intensification and modernisation processes.

Table 1

Carbon footprint by country, at farm gate, in the period 2014–2018 (Kt CO_2eq)

	Member state	2014	2015	2016	2017	2018	Total 2014–2018
1	Austria	9,238.31	9,313.71	9,325.39	9,250.03	8,909.83	46,037.27
2	Belgium	12,411.72	12,598.42	12,608.08	12,321.85	12,363.75	62,303.82
3	Bulgaria	6,889.27	6,929.04	7,095.34	7,063.93	6,980.59	34,958.17
4	Croatia	3,445.82	3,461.17	3,416.82	3,534.37	3,432.92	17,291.10
5	Cyprus	572.68	593.33	622.43	640.79	626.07	3,055.30
6	Czech Rep.	8,767.06	9,164.03	9,261.68	9,008.34	8,743.23	44,944.34
7	Denmark	15,800.78	15,971.73	15,957.74	15,792.90	15,539.29	79,062.44
8	Estonia	8,053.58	8,091.81	7,898.98	7,966.12	7,894.64	39,905.13
9	Finland	21,425.74	21,529.05	21,625.37	21,679.08	21,887.85	108,147.09
10	France	96,679.80	97,328.39	95,276.52	95,904.10	94,241.52	479,430.33
11	Germany	106,353.24	104,661.82	103,496.23	101,803.39	98,752.94	515,067.62

Table 1 (continued)

12	Greece	11,294.99	11,008.70	11,106.95	11,363.51	10,574.56	55,348.71
13	Hungary	14,772.05	14,794.37	15,455.42	15,328.60	15,542.30	75,892.74
14	Ireland	36,390.96	36,623.09	37,504.25	38,084.21	35,905.31	184,507.82
15	Italy	43,606.92	44,174.73	44,707.33	44,805.21	44,635.23	221,929.42
16	Latvia	8,734.53	8,843.30	8,787.65	8,768.74	8,611.29	43,745.51
17	Lithuania	15,770.71	15,856.59	15,651.26	15,579.88	15,268.75	78,127.19
18	Luxembourg	750.09	761.04	782.46	782.54	750.21	3,826.34
19	Malta	116.00	111.47	112.00	112.91	131.65	584.03
20	Netherlands	39,498.52	40,942.82	40,908.33	39,976.44	39,677.14	201,003.25
21	Poland	76,309.89	75,928.82	77,209.25	79,207.22	78,552.01	387,207.19
22	Portugal	9,099.20	9,292.22	9,285.22	9,648.09	9,174.42	46,499.15
23	Romania	17,302.30	17,792.84	17,866.94	18,262.00	18,835.06	90,059.14
24	Slovakia	3,069.92	2,944.76	3,050.23	2,874.69	2,902.98	14,842.58
25	Slovenia	2,065.22	2,076.62	2,111.13	2,107.97	2,061.95	10,422.89
26	Spain	50,088.91	51,250.79	51,429.48	52,125.87	51,230.28	256,125.33
27	Sweden	18,355.79	18,217.23	18,287.45	18,432.67	18,555.66	91,848.80

Source: data processed by the author, FAO, 2025.

A notable feature of the dataset is the strong correlation between total emissions and the structural size of national agricultural sectors rather than emission intensity alone. Large agricultural economies (*e.g.*, France, Germany, Spain, Poland) dominate absolute emissions, whereas smaller or less intensive systems contribute marginal shares to the EU total. This highlights a key methodological consideration in environmental assessment: absolute emissions must be interpreted alongside intensity indicators (*e.g.*, emissions per hectare or per unit of output) to avoid biased policy conclusions.

From a systems perspective, the data also reflect the persistence of livestock-driven emissions in Western Europe (particularly methane from enteric fermentation and manure management) and fertiliser-driven emissions in intensive arable systems. This dual emission structure underscores the complexity of mitigation pathways, which must simultaneously address biological and chemical emission sources.

Overall, the period 2014–2018 illustrates a relatively stable but highly heterogeneous agricultural emissions landscape in the EU-27. While incremental efficiency gains and policy interventions under the Common Agricultural Policy are observable, the structural composition of European agriculture continues to be the dominant determinant of carbon footprint distribution, reinforcing the need for differentiated, region-specific mitigation strategies rather than uniform reduction targets.

At aggregate level, **in the period 2019–2023**, Germany (477,530.89 kt CO_2eq) and France (447,978.42 kt CO_2eq) continue to dominate the EU agricultural emissions profile, although both countries exhibit a clear downward trend over the period, particularly after 2021. This decline is indicative of structural efficiency

gains, gradual livestock herd adjustments, and improved nitrogen management practices. Poland (383,289.94 kt CO_2eq) remains a key high-emission Member State, with relatively stable emissions, reflecting a balance between agricultural intensification and partial efficiency improvements. Spain (257,178.95 kt CO_2eq) and Italy (221,592.10 kt CO_2eq) also maintain high emission levels, although they both exhibit moderate downward adjustments in the final years of the series, suggesting incremental decarbonisation without structural transformation.

A notable feature of the 2019–2023 period is the more pronounced declining trajectory observed in several Western European countries, particularly the Netherlands (from 39,890.71 kt CO_2eq in 2019 to 34,949.90 kt CO_2eq in 2023), Belgium, and France. These reductions are consistent with intensified environmental regulation, nitrogen emission mitigation policies, and livestock density constraints, especially in highly intensive agricultural systems. Similarly, Austria and Denmark show gradual downward adjustments, reflecting continued efficiency gains in input use and improved manure management systems.

In contrast, several Central and Eastern European Member States, including Romania, Bulgaria, and Latvia, display relatively stable emission patterns with minor fluctuations. Romania (89,254.85 kt CO_2eq) shows a slight reduction compared to the beginning of the period but maintains a structurally stable emissions profile, indicating limited structural transformation in livestock systems and fertiliser use efficiency. This stability suggests that emissions are primarily driven by biological processes and input intensity rather than by abrupt policy-induced changes.

Northern European countries such as Finland and Sweden maintain relatively stable or slightly increasing emission trends. In Finland (111,508.97 kt CO_2eq), emissions remain consistently high due to the structural importance of livestock systems, particularly dairy production, while Sweden shows marginal variability, reflecting stable but high-input agricultural systems with relatively advanced environmental management practices.

From a systemic perspective, the dataset highlights a strengthening divergence between Western/Northern Europe, where emissions are increasingly shaped by regulatory constraints and efficiency-oriented mitigation strategies, and Eastern Europe, where emissions remain more closely tied to structural agricultural characteristics and slower technological convergence. Importantly, despite observable reductions in several Member States, the overall EU agricultural sector continues to exhibit strong path dependency, with emissions largely determined by livestock density, fertiliser dependence, and energy-intensive production systems.

Table 2

Carbon footprint by country, at farm gate, in the period 2019–2023 (Kt CO_2eq)

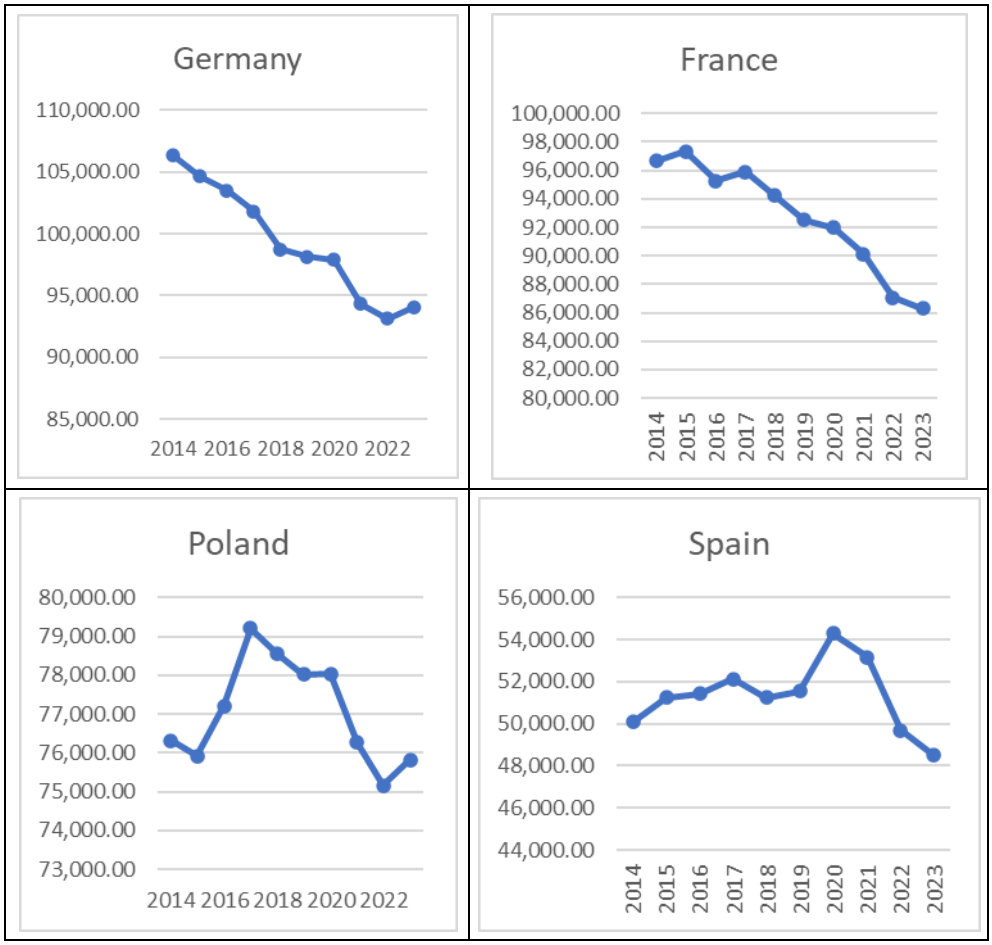
	Member state	2019	2020	2021	2022	2023	Total 2019–2023
1	Austria	8,765.13	8,920.22	8,821.38	8,726.83	8,611.05	43,844.61
2	Belgium	12,715.17	12,440.92	12,330.31	11,830.99	11,496.81	60,814.20
3	Bulgaria	7,048.87	7,202.33	7,101.83	6,856.77	6,873.37	35,083.17
4	Croatia	3,426.45	3,460.40	3,448.52	3,267.88	3,160.91	16,764.16
5	Cyprus	626.98	676.30	668.40	622.75	501.78	3,096.21
6	Czech Rep.	8,722.34	8,441.57	8,549.70	8,682.12	8,113.46	42,509.19
7	Denmark	15,604.32	15,759.65	15,426.35	14,918.37	14,596.94	76,305.63
8	Estonia	7,879.30	7,883.19	7,832.72	7,835.37	7,777.16	39,207.74
9	Finland	22,347.17	22,455.77	22,353.64	22,132.16	22,220.23	111,508.97
10	France	92,522.79	91,974.47	90,148.33	87,045.43	86,287.40	447,978.42
11	Germany	98,132.16	97,883.79	94,324.16	93,137.46	94,053.32	477,530.89
12	Greece	10,460.56	10,550.51	10,730.97	9,836.86	10,175.47	51,754.37
13	Hungary	15,566.15	15,875.45	15,691.58	14,493.71	14,341.88	75,968.77
14	Ireland	35,684.73	35,798.46	36,244.76	35,944.53	35,369.55	179,042.03
15	Italy	44,276.52	45,530.19	44,629.48	43,682.60	43,473.31	221,592.10
16	Latvia	8,726.52	8,844.27	8,800.25	8,800.88	8,680.95	43,852.87
17	Lithuania	15,354.11	15,440.01	15,398.15	15,134.34	15,041.35	76,367.96
18	Luxembourg	751.09	757.81	754.98	721.91	713.38	3,699.17
19	Malta	142.29	145.44	140.77	156.26	158.30	743.06
20	Netherlands	39,890.71	39,152.87	38,500.50	35,057.53	34,949.90	187,551.51
21	Poland	78,016.75	78,029.59	76,266.69	75,155.36	75,821.55	383,289.94
22	Portugal	9,335.83	9,715.37	9,412.17	8,900.00	8,779.55	46,142.92
23	Romania	18,637.14	17,737.56	18,322.08	17,311.09	17,246.98	89,254.85
24	Slovakia	2,875.85	2,848.92	2,769.65	2,638.43	2,620.48	13,753.33
25	Slovenia	2,081.78	2,085.85	2,089.69	2,012.88	1,980.77	10,250.97
26	Spain	51,557.72	54,282.80	53,161.71	49,683.45	48,493.27	257,178.95
27	Sweden	19,008.15	18,847.75	18,683.81	18,745.10	18,567.29	93,852.10

Source: Data processed by the author, FAO, 2025.

Overall, the period 2019–2023 reflects a transitional phase in EU agricultural decarbonisation. While policy frameworks have begun to produce measurable emission reductions in highly intensive systems, the aggregate structure of agricultural production remains the dominant driver of emissions. Consequently, the data suggest that further mitigation will require not only efficiency improvements, but also deeper structural changes in livestock systems, nutrient management, and farm specialisation patterns across Member States.

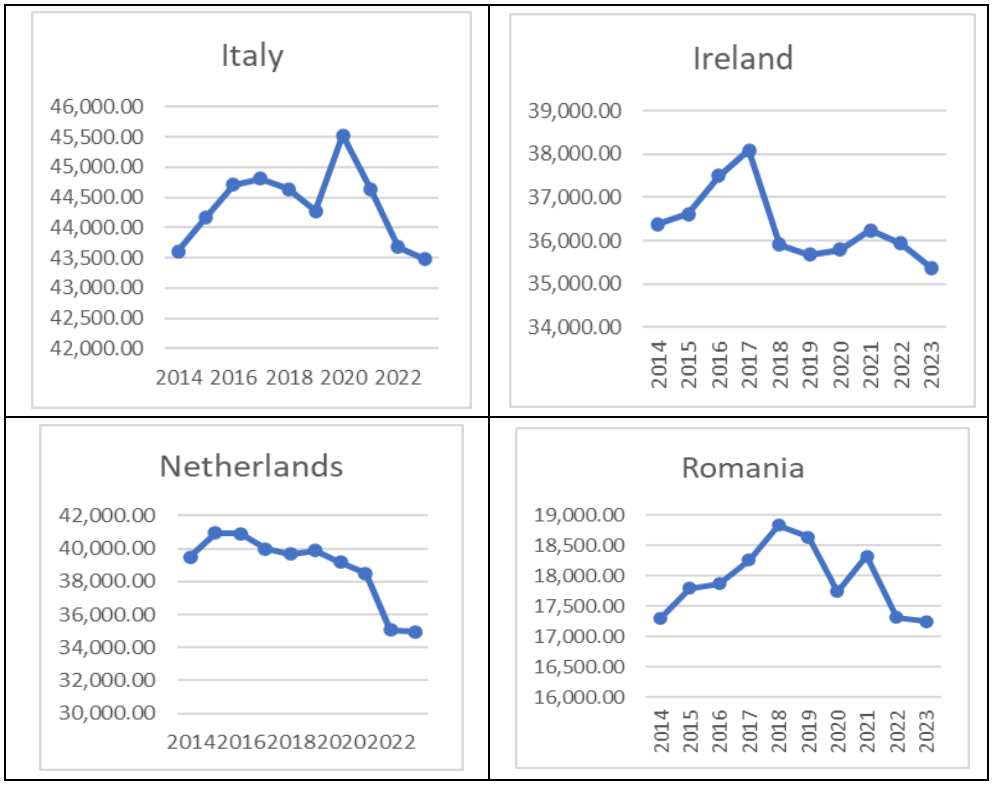
The evolution of the farm-gate carbon footprint across selected EU-27 Member States over **the period 2014–2023** includes emissions from enteric fermentation (livestock), manure management, soil-related agricultural emissions (fertiliser use), on-farm energy consumption. Large structural differences between countries have to be mention **(**countries with intensive livestock systems *e.g.*, Ireland, the Netherlands have higher values).

While the period 2014–2018 is a relatively stable period, with small interannual variations, agriculture is still largely dependent on conventional models (mineral fertilisers, fossil energy), in the period 2019–2023 two clearer patterns emerge: decline in some countries (efficiency gains, climate policies, agricultural digitalisation) and stagnation or slight increases in others (intensification or climate variability effects).



Source: Data processed by the author, FAO, 2025.

Figure 2. The evolution of carbon footprint at farm-gate in selected EU-27 Member States (Kt CO_2eq).



Source: Data processed by the author, FAO, 2025.

Figure 3. The evolution of carbon footprint at farm-gate in selected EU-27 Member States (Kt CO_2eq).

Analysing the differences between country patterns, it is important to note that:

- Production intensity is the main driver of carbon footprint levels,
- The major variations are explained by sectoral structure (livestock *versus* crop production),
- National agricultural policies and CAP can influence emission reductions,
- Carbon efficiency (emissions per unit of output) becomes the key performance indicator.

A key analytical insight emerging from the dataset is the asymmetry between high-emission and low-emission agricultural systems. Large agricultural economies not only dominate absolute emission levels but also contribute most significantly to the observed reductions, suggesting that mitigation policies are increasingly effective in systems where emissions are structurally concentrated and where technological efficiency gains yield measurable impacts. Conversely, smaller or structurally less intensive agricultural systems exhibit limited variation, indicating a lower responsiveness to policy instruments and technological change.

From a systems transition perspective, the observed patterns confirm that EU agricultural decarbonisation is primarily driven by incremental efficiency improvements rather than radical structural transformation. Emission reductions are most pronounced in regions characterised by high input intensity and regulatory pressure, while stability persists in regions where agricultural systems are extensive, fragmented, or less technologically advanced.

Overall, the comparative analysis of the two periods confirms a partial but uneven decoupling between agricultural production and greenhouse gas emissions across the EU-27. While significant progress has been achieved in several Member States, the persistence of stable or increasing trends in others underscores the need for differentiated mitigation strategies that account for structural heterogeneity, production specialisation, and region-specific constraints within European agricultural systems.

4.3. COMPARATIVE DEVELOPMENTS

In order to compare the situation between different member states, the Carbon Footprint in t CO_2/capita or total kt per country cannot be simply used. Not all the member states have the same "importance" when calculating Carbon Footprint. This is the reason why a Simple Average cannot be used like it was used for aggregated data per country in Table 1 and Table 2, respectively:

Simple Arithmetic Mean for each member state EU-27 Carbon Footprint = $\frac{\sum_{i=1}^{n} x_i}{n}$, where:

x_i = Carbon Footprint/year/country

n = number of years (5 years for the periods 2014–2018 and 2019–2023 or 10 years for 2014–2023).

For a meaningful result, a weighted average has to be used, such as:

$$\textbf{Weighted average for EU-27} = \frac{\sum(\mathbf{xi} \cdot \mathbf{pi})}{\sum \mathbf{pi}}$$

where: x_i could be the Carbon Footprint per state estimated as kt CO_2/capita,

p_i could be the population or other relevant factor such as GDP.

For the purpose of this study, in order to have a significant result, x_i is Carbon Footprint calculated by country, at farm gate, as an average for 5 years (2014–2018 or 2019–2023), in Kt CO_2eq (AR5), based on Table 1 and Table 2. Consequently, a correct coefficient for this weighted average would be p_i = Utilised Agricultural Area (UAA) by country (ha).

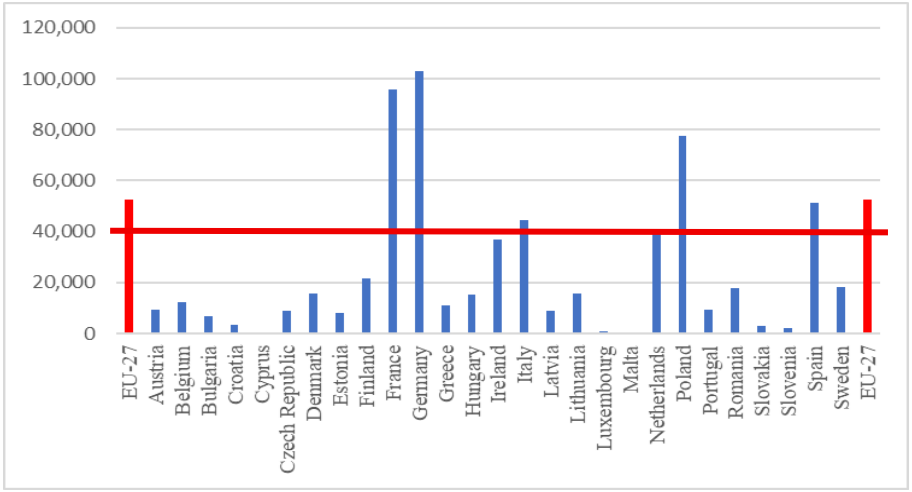
Table 3

Calculations for EU-27 average carbon footprint at farm gate

	Member state	**2014–2018 average**	**2019–2023 average**	**2014–2018 numerator**	**2019–2023 numerator**	**Denominator (UAA)**
		Kt CO_2eq	Kt CO_2eq	Kt CO_2eq/ thou ha	Kt CO_2eq/ thou ha	million ha
1	Austria	9,207.45	8,768.92	23.94	22.80	2.60
2	Belgium	12,460.76	12,162.84	17.07	16.66	1.37
3	Bulgaria	6,991.63	7,016.63	31.88	32.00	4.56
4	Croatia	3,458.22	3,352.83	4.25	4.12	1.23
5	Cyprus	611.06	619.24	0.08	0.08	0.13
6	Czech Rep.	8,988.87	8,501.84	31.37	29.67	3.49
7	Denmark	15,812.49	15,261.13	41.59	40.14	2.63
8	Estonia	7,981.03	7,841.55	7.78	7.65	0.98
9	Finland	21,629.42	22,301.79	49.32	50.85	2.28
10	France	95,886.07	89,595.68	2,623.44	2,451.34	27.36
11	Germany	103,013.52	95,506.18	1,707.96	1,583.49	16.58
12	Greece	11,069.74	10,350.87	31.00	28.98	2.80
13	Hungary	15,178.55	15,193.75	74.53	74.60	4.91
14	Ireland	36,901.56	35,808.41	165.69	160.78	4.49
15	Italy	44,385.88	44,318.42	532.63	531.82	12.00
16	Latvia	8,749.10	8,770.57	17.24	17.28	1.97
17	Lithuania	15,625.44	15,273.59	45.47	44.45	2.91
18	Luxembourg	765.27	739.83	0.10	0.10	0.13
19	Malta	116.81	148.61	0.00	0.00	0.01
20	Netherlands	40,200.65	37,510.30	73.17	68.27	1.82
21	Poland	77,441.44	76,657.99	1,139.16	1,127.64	14.71
22	Portugal	9,299.83	9,228.58	36.64	36.36	3.94
23	Romania	18,011.83	17,850.97	229.29	227.24	12.73
24	Slovakia	2,968.52	2,750.67	5.52	5.12	1.86
25	Slovenia	2,084.58	2,050.19	1.01	0.99	0.48
26	Spain	51,225.07	51,435.79	1,222.23	1,227.26	23.86
27	Sweden	18,369.76	18,770.42	54.93	56.12	2.99
	EU-27	---	---	8,167.28	7,845.80	**154.82**

Source: data processed by the author, FAO, 2025.

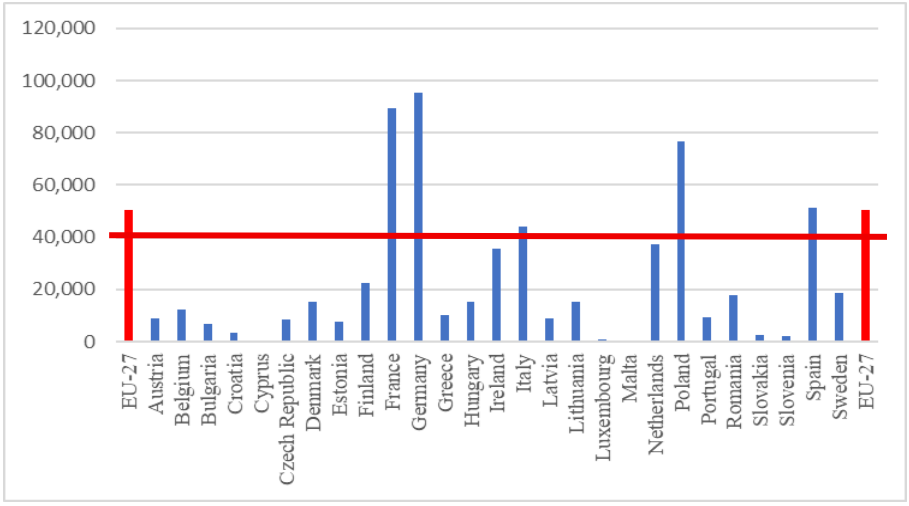
Total numerator for EU-27 (2014–2018) = 8,167,284 Kt CO_2eq
Total numerator for EU-27 (2019–2023) = 7,845,806 Kt CO_2eq
Total denominator (2014–2023) = 154.82 million ha UAA
EU-27 average carbon footprint at farm gate (2014–2018) =
= 8,167,284 Kt CO_2eq (AR5) / 154,82 million ha UAA = 52,752 Kt CO_2eq (AR5)
EU-27 average carbon footprint at farm gate (2019-2023) =
= 7,845,806 Kt CO_2eq (AR5) / 154.82 million ha UAA = 50,675 Kt CO_2eq (AR5)



Source: Data processed by the author, FAO, 2025.

Figure 4. Average carbon footprint at farm gate in EU-27 for the period 2014–2018 (Kt CO_2eq).

Comparing the results from Figures 4 and 5, it can be pointed out that Average carbon footprint at farm gate in EU-27 for the period 2019–2023 as compared to the period 2014–2018, decreased 2 million tonnes CO_2eq (AR5) from 52.7 Mt to 50.6 Mt. Most member states are under this average. Only 4 countries reach or exceed this average: Germany, France, Poland and Spain. They have a declining trend from the period 2014–2018 to the period 2019–2023. Significant results are also found in Italy, Netherlands and Ireland.



Source: Data processed by the author, FAO, 2025.

Figure 5. Average carbon footprint at farm gate in EU-27 for the period 2019–2023 (Kt CO_2eq).

At aggregate level, there are differentiated trajectories of decarbonisation, reflecting heterogeneous policy impacts, technological adoption rates, and structural characteristics of national agricultural systems. The data indicate a general tendency towards emission reduction in most Western and high-output agricultural economies. Germany (-7,507.35 kt CO_2eq) and France (-6,290.38 kt CO_2eq) exhibit the most significant absolute decreases, reflecting sustained improvements in nitrogen use efficiency, gradual livestock adjustment, and increasing compliance with environmental regulations under the Common Agricultural Policy (CAP) and the European Green Deal framework. Similarly, the Netherlands (-2,690.35 kt CO_2eq), Ireland (-1,093.16 kt CO_2eq), Denmark (-551.36 kt CO_2eq), and Austria (-438.53 kt CO_2eq) demonstrate consistent downward trends, consistent with intensified mitigation efforts in highly intensive livestock and mixed farming systems.

In contrast, certain Member States display either stable or slightly increasing emission trajectories. Finland (+672.38 kt CO_2eq) and Sweden (+400.66 kt CO_2eq) show moderate increases, which can be attributed to structural resilience of livestock-based systems and relatively stable production intensities rather than policy reversals. Spain (+210.72 kt CO_2eq) also records a marginal increase, reflecting variability in crop production systems and climatic sensitivity affecting input requirements. Bulgaria (+25.00 kt CO_2eq), Cyprus (+8.18 kt CO_2eq), Hungary (+15.21 kt CO_2eq), and Latvia (+21.47 kt CO_2eq) remain broadly stable, indicating limited structural change and a slow convergence towards EU average mitigation trajectories.

The integrated analysis of carbon footprint at farm-gate in the period 2014–2023 highlights a series of fundamental conclusions with direct relevance for the design of modern and efficient environmental policies adapted to the specific characteristics of the agricultural sector. The analysis emphasises the importance of precision agriculture, renewable energy integration, improved manure management, and carbon accounting systems at farm level.

Even though the paper presents “farm-gate” data and does not include the full food supply chain (transport, processing, consumption) and comparability between countries may be affected by differences in reporting methodologies, farm structure and climate and agricultural productivity conditions, the main conclusions could be used as a valuable input for the new environmental policies.

5. CONCLUSIONS

The findings of the study suggest that future environmental policies should move beyond compliance-oriented approaches and focus increasingly on carbon-efficiency strategies aimed at reducing emissions per unit of agricultural output rather than targeting only absolute emission reductions. The analysis also demonstrates the determining role of agricultural inputs in shaping emission dynamics. In particular, nitrogen fertilisers represent the main source of emissions in the crop

sector, while their evolution closely mirrors the broader economic and structural transformations experienced by agriculture. This highlights the importance of integrating economic policy instruments into environmental governance. Such measures may include differentiated taxation for high-carbon-intensity inputs, financial support for high-efficiency fertilisers, and the broader adoption of precision agriculture technologies capable of optimising input use and reducing environmental pressures.

Another significant conclusion relates to the pronounced structural inertia of the livestock sector. The relatively stable share of emissions generated by enteric fermentation indicates limited progress in reducing biologically driven emissions. Furthermore, the observed reductions in emissions appear to have resulted primarily from decreases in livestock numbers rather than from substantial technological innovation or efficiency improvements. At the same time, the limited implementation of manure valorisation technologies, such as biogas production systems, reflects the insufficient modernisation of waste management infrastructure in agriculture. Consequently, there is a clear need for policies that encourage technological innovation through optimised feed systems, anti-methanogenic additives, investments in manure management infrastructure, and the promotion of circular economy practices at farm level.

The findings additionally reveal that the energy transition within agriculture remains incomplete. Although emissions associated with energy consumption have significantly declined, the sector continues to rely heavily on fossil fuels, particularly petroleum products, which accounted for nearly 70% of energy-related emissions after 2020. This persistent dependence underlines the necessity of accelerating the decarbonisation of agricultural energy systems through the electrification of agricultural machinery, the integration of renewable energy sources such as photovoltaic systems and biogas installations, and the implementation of dedicated support mechanisms for low-carbon mechanisation technologies.

The influence of policies promoted by the European Commission, including the Common Agricultural Policy and the European Green Deal, has also contributed to measurable progress in reducing environmentally harmful practices, improving technological efficiency, and strengthening emissions monitoring systems. Nevertheless, the impact of these policies remains heterogeneous and often insufficient, particularly among small and medium-sized farms that face limited financial and technological capacities. This indicates the necessity of adopting differentiated policy frameworks tailored to farm typologies in order to avoid increasing sectoral polarisation and unequal access to sustainability transitions.

At the same time, the study highlights important methodological and data-related limitations, particularly the reliance on aggregated datasets and the lack of detailed micro-level information. These constraints emphasise the need for a new policy paradigm based on digitalisation, real-time monitoring systems, and the integration of analytical models aligned with methodologies developed by the

Intergovernmental Panel on Climate Change. In this context, the implementation of farm-level carbon accounting systems becomes essential for improving subsidy allocation mechanisms, facilitating the development of carbon farming schemes, and enabling agricultural participation in emerging carbon markets.

This involves integrating climate considerations into economic decision-making processes and ensuring that environmental objectives are aligned with broader goals related to food security, economic resilience, and sustainable rural development. In this context, estimating the carbon footprint at farm level is not merely an analytical exercise but becomes a central strategic tool for designing new environmental policies capable of supporting the transition towards a competitive, resilient, and climate-neutral agriculture.

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