

Sustainable Dairy Farming in the Visegrad Group Countries' Regions: Linking Eco-Efficiency and Competitiveness

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Abstract

This study evaluates regional eco-efficiency and market competitiveness in the dairy sector of the Visegrad Four (V4) regions – Czechia, Slovakia, Hungary, and Poland – for 2015 and 2022. Eco-efficiency was assessed using input-oriented Data Envelopment Analysis (DEA) with an undesirable output, assuming constant returns to scale, while competitiveness was measured with a composite Dairy Competitiveness Index based on economic and sectoral indicators. Results indicate that high environmental performance does not consistently align with market competitiveness, with only the Polish region PL92: Mazowiecki regionalny excelling in both dimensions. The research hypothesis – The eco-efficiency of a region ensures a higher level of outputs for given inputs, thereby increasing its competitiveness – was rejected. Four regional groups were identified – Leaders, Market-driven, Eco-driven, and Laggards – highlighting persistent structural differences across the V4. The findings provide evidence for designing region-specific policies that support sustainable, competitive, and resilient dairy systems.

Keywords

dairy eco-efficiency, competitiveness, V4 regions, interrelationship

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INTRODUCTION

The dairy sector represents one of the most important areas of agricultural production in the European Union. Its significance lies not only in the volume of production or its contribution to food security, but

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it also has a broad influence on rural economies, employment opportunities, and trade performance of the EU member states. The dairy sector is closely linked to the agricultural sustainability, regional economic growth and cohesion, and the stability of rural areas particularly in areas with limited alternative economic opportunities.

Following the removal of milk quotas in 2015, the EU dairy sector expanded as producers gained greater flexibility to adjust output to market conditions. Since then, milk production has continued to grow, stimulated by the intensification of dairy farming, the use of high-quality concentrated feeds, advances in breeding programmes, improvements in herd and feed management, better livestock housing, and the increasing adoption of technologies such as automated milking systems. This upward trend has been reinforced over the last decades by the Common Agricultural Policy (CAP), which in its 2023–2027 framework prioritises strengthening the competitiveness of companies, regions, and countries in response to rising global demand and the need to support world dairy markets (European Commission, 2023). However, while productivity has accelerated through the shift toward larger and more automated facilities, these developments have also raised concerns regarding environmental impacts, animal welfare, and the overall sustainability of the dairy sector (Heise & Theuvsen, 2018; Autio et al., 2023). In particular, the dairy industry represents one of the primary sources of agricultural greenhouse gas (GHG) emissions—mainly methane and nitrous oxide – resulting from enteric fermentation, manure management, and feed production (FAO, 2001). Therefore, sustainability and environmental concerns have become central themes in public debate and scientific discourse and are now integral to government agendas. The global dairy industry is increasingly facing pressure to address these challenges (Bhat, 2025). Achieving economic sustainability in the dairy sector depends on establishing a durable competitive position in the market, where the adoption of advanced technologies, precision farming practices, and value-added product innovations can enhance productivity and boost market competitiveness (Agostinho et al., 2019). Moreover, agricultural production in general is confronted with a range of long-term sustainability risks, including the need to increase output while simultaneously mitigating the negative environmental consequences associated with agricultural activities (Arru et al., 2024). In this context, advancing towards more sustainable dairy systems requires a shift to practices that integrate environmental protection with improved resource-use efficiency and long-term sector resilience (Brito et al., 2021). Therefore, assessing eco-efficiency becomes essential, as it provides a comprehensive framework for evaluating how effectively the dairy sector can balance economic performance with environmental responsibility. Most existing studies examine dairy eco-efficiency at the farm level within a single country (Urdiales et al., 2016; Grassauer et al., 2022; Martinsson & Hansson, 2021; Baležentis et al., 2022; Novaković et al., 2025). However, from the perspective of the common EU cohesion policy, it is necessary to analyse the dairy sector also for larger territorial units and make international comparisons. The dairy sectors vary among regions within each nation. European regions are characterised by different environmental conditions, market conditions, consumer behaviour, and policy environment, which inevitably affect the structure of their dairy farming (Bianchi et al., 2020, Thorsøe et al., 2020). Thus, evaluating dairy eco-efficiency regionally is important, yet studies at this level remain limited.

At the same time, it is necessary to monitor the sector's market position from the perspective of competitiveness, to capture the potential synergies between economic viability and ecological sustainability. Aligning economic incentives with environmental objectives allows dairy producers to implement practices that ensure both profitability and ecological performance (Gardašević et al., 2024). While Latruffe (2010) notes that efficiency is often cited as an indicator of competitiveness, the potential ecological dimension is not considered. According to Pietrzak et al. (2023), a significant research gap exists regarding the integration of competitiveness and eco-efficiency analyses in dairy cooperatives. Few studies address the link between eco-efficiency and competitiveness in the dairy sector; however, these are primarily limited to farm-level analyses within individual countries (Menning and Szigeti, 2025; Arru, et al., 2024;

Pietrzak et al., 2023; Zhu et al, 2023; Grzelak et al., 2022; Lioy et al., 2022). Therefore, our paper focuses on assessing regional dairy eco-efficiency together with competitiveness in the dairy market, to simultaneously analyse the relationship between them. Based on Lioy et al.' argument (2022) that, at the farm level, high environmental performance is both an advantage in terms of economic competitiveness and a prerequisite for optimal economic outcomes, we formulate the following research hypothesis: *The eco-efficiency of a region ensures a higher level of outputs for given inputs, thereby increasing its competitiveness.*

Eco-efficiency and competitiveness are evaluated for two years, 2015 and 2022, to compare changes over time. The year 2015 was chosen as the starting point of the analysis, as it marks the abolition of milk quotas and allows capturing their impacts. The year 2022 was selected because it is the most recent year for which the analysed data are available. The analysis focuses on the NUTS2 regions within the Visegrad Four, i.e. Czechia, Slovakia, Hungary, and Poland. Svatoš et al. (2013) highlight that comparing the agricultural sectors of the Visegrad countries is meaningful, as the economic structures of the V4 members have undergone substantial changes over time, with agriculture being among the most affected sectors. Agricultural production in the V4 experienced two major shocks: first in the 1990s, due to the transition from centrally planned to market economies, and later through integration into the European Union.

Dairy eco-efficiency is assessed using an input-oriented Data Envelopment Analysis (DEA) model under the assumption of constant returns to scale.

The paper is structured as follows. First, the concepts of eco-efficiency and competitiveness are introduced, along with a review of relevant literature. Second, the data and methodologies used to assess dairy eco-efficiency and competitiveness are described, including the CCR DEA model, the super-efficiency DEA model, and the construction of a composite index. In the third section, the results are presented and compared with findings from other studies. Finally, the article discusses key findings, limitations, and offers suggestions for future research.

1 LITERATURE SURVEY

The European Commission (EC) wants European food production to be a global example of sustainability through several initiatives, such as the EU Green Deal, the Farm to Fork (F2F) and Biodiversity Strategies, Horizon Europe, Next Generation EU, and the Common Agricultural Policy (CAP). These initiatives aim to support a fair transition (by promoting cooperation between different sustainability goals and reducing conflicts among them. For example, the CAP 2023–2027 focuses on fighting climate change, protecting the environment, and preserving landscapes and biodiversity, while also supporting rural communities, ensuring fair incomes for farmers, improving competitiveness, and strengthening farmers' role in the food chain (European Commission, 2021, 2023). Similarly, the Farm to Fork (F2F) strategy seeks to take advantage of the economic benefits of moving towards more sustainable practices and to create win-win opportunities that enhance both sustainable development and farm profitability, reflecting the synergy between environmental and economic aspects of farming (Mowlds, 2020). To support the successful transformation of the dairy sector, it is essential to develop methods that capture the multiple dimensions of sustainability and consider the interactions between them, providing a practical and usable framework for decision-making at all levels (Dumanski et al., 1998). One of the most used approaches for assessing the environmental dimension of farming is the evaluation of production eco-efficiency, which serves as a basis for linking sustainability with economic performance (UNESCAP, 2009).

The concept of eco-efficiency was first introduced by Schaltegger & Sturm (1990) as a „business link to sustainable development”. Eco-efficiency, often described as the integration of economic and ecological objectives, became popular in the 1990s to attain long-term agricultural growth (Gołaś et al., 2020). The concept of eco-efficiency is applicable to different products and sectors, as well as at different levels (Caiado et al., 2017).

Measuring the efficiency of the dairy sector is important not only for improving dairy cow yield performance, but also for enhancing the efficiency of other resources and increasing the incomes of individual dairy farms (Kovács & Szücs, 2020). There are several methods used to quantify eco-efficiency performance, with the ratio approach and the frontier approach in the foreground (Liu et al., 2020; Bianchi et al., 2020). Due to the need to consider multiple input and output variables, as well as to account for the negative aspects of agriculture as undesirable outputs, Data Envelopment Analysis is often preferred (Dyckhoff & Allen, 2001).

A number of studies have applied various DEA approaches (Adenuga et al., 2018; Cecchini et al., 2018; Graussauer et al., 2022; Baležentis, 2022; Novaković et al., 2025; Cortés et al., 2021; Martinsson & Hansson, 2021; Soteriades et al., 2020) and parametric stochastic frontier analysis (Alem, 2023a, 2023b; Le et al., 2020) to evaluate the environmental efficiency of dairy production at the farm level within a single country. Efficiency analysis can also be used to assess only the economic dimension of dairy production; however, in this case it refers solely to economic sustainability, without considering environmental aspects (Špička & Smutka, 2014; Špička, 2015; Špička & Machek, 2015; Náglová & Rudinskava, 2021; Žáková Kroupová et al., 2020; Kovács & Szücs, 2020). In addition, insights from efficiency measurement may be linked with market competitiveness analyses, as both perspectives offer complementary information on performance and resource use within the dairy sector, even though they capture different aspects of sectoral dynamics. Fostering competitiveness of the dairy sector at the national, regional and farm levels is one of the objectives of the CAP 2023–2027. Competitiveness represents the ability of a specific geographical area to stimulate economic growth and enhance social prosperity through the efficient use of resources and improvements in the quality of life of its inhabitants (Judrupa, 2021). A few studies have assessed the competitiveness of the dairy sector at the macro level, applying individual indicators, aggregated indicators and composite indices (Bojnec & Fertó, 2014; Irz & Jansik, 2015; Simo et al., 2016; Nagy & Jámboř, 2019; Parzonko et al., 2024).

Achieving synergy between economic performance and ecological sustainability represents both a challenge and an opportunity for the dairy sector (Britt et al., 2018). Aligning economic incentives with environmental goals allows producers to adopt models that support long-term profitability while reducing environmental impacts (Gardašević et al., 2024). However, ensuring both dimensions of sustainability remains a complex, multidimensional task requiring integrated strategies, stakeholder cooperation, and innovation (Brkić & Puvača, 2024). Studies emphasise the need to improve resource efficiency, minimise environmental impacts, and maintain economic viability (Bi et al., 2024), while also addressing challenges related to technology adoption and diverse regional conditions across the EU (Arvidsson Segerkvist et al., 2020; Penker, 2024). These pressures place eco-efficiency and competitiveness at the forefront of priorities for both producers and policymakers.

Despite growing interest in both eco-efficiency and competitiveness, current research rarely examines these two dimensions simultaneously at the regional level. Many existing studies rely on national averages or evaluate environmental and economic outcomes separately, overlooking substantial regional differences in production conditions, market dynamics, and policy impacts. This leaves a gap in understanding how regions position themselves in terms of both environmental performance and economic strength. By analysing these aspects within a unified regional framework, this study offers evidence that can support more targeted, region-specific policy measures and improve the alignment between sustainability and competitiveness objectives.

2 METHODOLOGY

Five input variables are selected: dairy cows per thousand inhabitants, live bovine per thousand inhabitants, employment in agriculture per thousand inhabitants, gross fixed capital formation in agriculture in € per capita, and compensation of employees in agriculture in € per capita. The output side includes

two desirable outputs: milk production in tons per cow and gross value added from agriculture in € per capita, and one undesirable output: greenhouse gas emissions in ton CO₂eq per 1 ton of milk. The selected input and output variables were chosen because they comprehensively capture the key determinants of dairy sector performance at the regional level. Inputs such as dairy cows, live bovine population, employment, capital formation, and labour compensation reflect the scale, labour, and capital intensity of dairy production, which are critical drivers of both productivity and economic output. The desirable outputs—milk production per cow and agricultural gross value added represent the economic efficiency and value creation of the sector, while the undesirable output, greenhouse gas emissions per ton of milk, accounts for its environmental impact. Together, these indicators allow for a multidimensional assessment of eco-efficiency, linking resource use and economic outcomes with sustainability, and are consistent with previous studies on agricultural and dairy sector efficiency (Song et al., 2012; Piao et al., 2019).

Data were obtained from EUROSTAT for the years 2015 and 2022, selected to allow a comparison over time. The year 2015 was chosen as the starting point of the analysis because it marks the abolition of milk quotas and allows capturing their impacts. The year 2022 was selected as it is the most recent year for which the analysed data are available. To ensure comparability under similar geographical conditions, the analysis focuses on the NUTS2 regions within the Visegrad Four: 8 Czech regions, 8 Hungarian regions, 17 Polish regions, and 4 Slovak regions.

The following research hypothesis is established: *The eco-efficiency of a region ensures a higher level of outputs for given inputs, thereby increasing its competitiveness.*

Descriptive statistics for the output variables are computed to enable a multidimensional comparison of the selected V4 regions (Coluccia et al., 2020; Cui et al., 2024).

A non-parametric frontier method originally proposed by Charnes, Cooper, and Rhodes in 1978 (Charnes et al., 1978), input-oriented Data Envelopment Analysis (DEA) assuming constant returns to scale, is used to assess dairy eco-efficiency in V4 regions. DEA applies linear programming to evaluate the relative efficiency or inefficiency of decision-making units (DMUs) that produce multiple outputs using multiple inputs. In this paper, DMUs correspond to the chosen V4 regions. DEA is a useful method to compile a complex efficiency indicator because no explicit weights are required (Dyckhoff & Allen, 2001). Nevertheless, the method has certain limitations – its outcomes are highly influenced by the selection of input and output variables, and the number of efficient DMUs on the frontier often rises as more variables are included (Laurinavičius & Rimkaviėnė, 2017).

Let's assume that we have n independent homogeneous decision-making units, denoted by DMU_j ($j = 1, 2, \dots, n$). For given p nondiscretionary inputs $Z_j = (z_{1j}, z_{2j}, \dots, z_{pj})^T$, each DMU consumes m discretionary inputs $X_j = (x_{1j}, x_{2j}, \dots, x_{mj})^T$ to produce s outputs $Y_j = (y_{1j}, y_{2j}, \dots, y_{sj})^T$ (Hua et al., 2007). Since greenhouse gas emissions represent an undesirable output, they should be converted into a positive one using an appropriate vector (w) (Seiford & Zhu, 2002).

$$y_j^{-b} = -y_j^b + w > 0 \quad (1)$$

$$y_j^{-b} = -y_j^b + \max(y_j^b) + 1 \quad (2)$$

The standard linear input-oriented CCR model with a constant return to scale and with undesirable output could be written as the following linear programming problem:

$$\text{Min } \theta_q$$

$$\sum_{j=1}^n y_{rj}^g \lambda_j \geq Y_{rq}^g, \quad r \in G(\text{desirable})$$

$$\sum_{j=1}^n y_{ij}^{-b} \lambda_j \geq Y_{iq}^{-b}, \quad t \in B(\text{undesirable}) \tag{3}$$

$$\sum_{j=1}^n x_{ij} \lambda_j \leq \theta X_{iq}, \quad i = 1, 2, \dots, m$$

$$\lambda_j \geq 0, \quad j = 1, 2, \dots, n$$

Where θ_q stands for the technical efficiency of the DMU $_q$ and λ_j represents the weight assigned to the DMU $_j$ ($j = 1, 2, \dots, n$).

To identifying the most efficient units among those considered efficient by standard DEA, Super-efficiency DEA model is used, and one additional condition is included in the original model: $\text{Min } \theta_q$

$$\sum_{j=1}^n y_{rj}^g \lambda_j \geq Y_{rq}^g, \quad r \in G(\text{desirable})$$

$$\sum_{j=1}^n y_{ij}^{-b} \lambda_j \geq Y_{iq}^{-b}, \quad t \in B(\text{undesirable}) \tag{4}$$

$$\sum_{j=1}^n x_{ij} \lambda_j \leq \theta X_{iq}, \quad i = 1, 2, \dots, m$$

$$\lambda_0 = 0$$

$$\lambda_j \geq 0, \quad j = 1, 2, \dots, m$$

To rank the V4 regions based on their competitiveness in the dairy sector, a Dairy Competitiveness Index is constructed for the years 2015 and 2022. The compilation of this composite index follows several steps, based on the *Manual on the Compilation of Composite Indicators* (OECD, 2008):

1. Adjustment to ensure consistent direction of development – undesirable outputs are transformed to reflect a positive orientation.
2. Standardization of variables – due to differing units of measurement, min-max standardization is used to standardize the variables to a common scale.
3. Determination of indicator weights – the weights of individual indicators are assigned based on Factor analysis. The weight of each indicator (variable) within its specific factor is based on its squared factor loading. Squaring the loadings avoids negative weights and represents the proportion of the variable's variance explained by that specific factor.

$$weight_{ij} = \frac{(Factor\ Loading_{ij})^2}{\sum_{k=1}^{n_i} (Factor\ Loading_{ik})^2} \tag{5}$$

where: $weight_{ij}$ – the calculated weight for the j -th variable within the i -th factor,

$Factor\ Loading_{ij}$ – the loading of the j -th variable on the i -th factor from rotated factor matrix with Varimax method,

$\sum_{k=1}^{n_i} (Factor\ Loading_{ik})^2$ – the sum of the squared factor loadings for all variables that load highly on the i -th factor/dimension.

4. Aggregation of indicators – the indicators are combined using the additive method into a single composite index according to the following formula:

$$I'_i = \sum_{j=1}^k v'_j U'_{ij} \quad (6)$$

where: I'_i – composite index value for region_{*i*} at time_{*t*},

v'_j – weight of indicator_{*j*} at time_{*t*},

U'_{ij} – standardized value of indicator_{*j*} for region_{*i*} at time_{*t*}.

The results of the leave-one-variable-out robustness test show that removing any single indicator does not lead to substantial changes in regional rankings. Only minor variations were observed, while the overall structure and relative positions of regions remained stable. This confirms that the composite indicator is not driven by any single variable and can be considered methodologically robust (Alqararah, 2023).

Pearson's correlation coefficient (r) is used to verify the existence and strength of the relationship between eco-efficiency and competitiveness in the dairy sector and to either accept or reject the established research hypothesis. The coefficient is calculated using the following formula:

$$r = \frac{Cov(x, y)}{S_{xy}} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (7)$$

where: r – Pearson's correlation coefficient,

x_i and y_i - individual values of the variables *eco-efficiency* (X) and *Dairy Competitiveness Index* (Y) for each V4 region,

\bar{x} and \bar{y} - mean values of *eco-efficiency* (X) and *Dairy Competitiveness Index* (Y) across all V4 regions,

n - number of regions compared.

To assess whether the observed relationship is statistically significant, a hypothesis test is conducted with the following null and alternative hypotheses:

H_0 : There is no relationship between the variables ($r = 0$),

H_1 : There is a relationship between the variables ($r \neq 0$).

The resulting p-value is compared with the significance level $\alpha = 0.05$. If p-value $< \alpha$, the null hypothesis is rejected, indicating a statistically significant relationship (Al-Hameed, 2022).

3 RESULTS

At the beginning of the results section, a multidimensional comparison of the V4 regions in terms of key agricultural output indicators, namely milk production, gross value added (GVA) from agriculture and greenhouse gas emissions (GHG) from agriculture, in two time periods 2015 and 2022. Basic descriptive statistics for key agricultural output indicators are presented in Table 1.

On average, between 2015 and 2022, milk production per cow and agricultural gross value added per capita increased in all V4 countries, reflecting overall improvements in productivity and economic performance. However, regional disparities widened, particularly in Hungary and Poland, where growth was uneven and driven by a few high-performing areas, while some regions experienced declines, especially in milk production. Even though overall agricultural greenhouse gas emissions in the V4 increased slightly, emissions in Czechia and Slovakia declined (except for the Slovak region SK02: Západné Slovensko). This overall increase was largely driven by rising emissions in most Hungarian and Polish regions. Hungary and Poland generally have a larger and more intensive livestock sector, which contributes

to higher methane emissions. Differences in agricultural policy dynamics also play a role, as environmental performance has improved more rapidly in Czechia and Slovakia, whereas production-driven growth has dominated in many Hungarian and Polish regions. These trends underscore the need for more balanced regional development and environmentally sustainable practices in the V4 dairy sector.

Table 1 Descriptive statistics for key output agricultural indicators

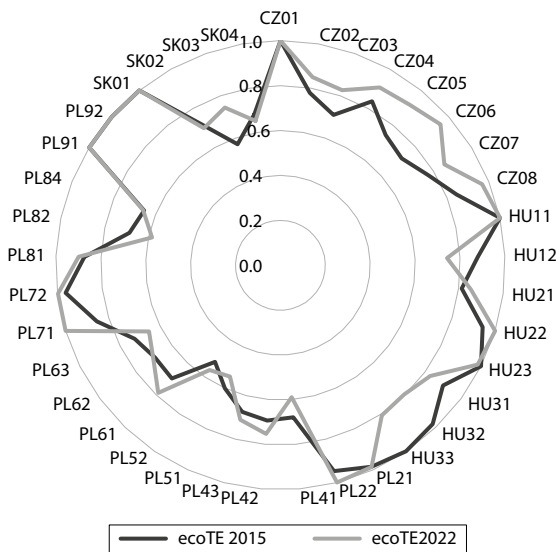
| Variable | MEAN | MEDIAN | STDEV | MIN | REGION 1/2 | MAX | REGION 2/2 |
|---------------|--------|--------|--------|-------|------------|----------|------------|
| Milk prod. 15 | 6.99 | 7.17 | 1.27 | 4.80 | PL21 | 8.84 | HU21 |
| Milk prod. 22 | 7.73 | 7.51 | 2.32 | 3.00 | PL43 | 16.20 | HU11 |
| GVA 15 | 346.00 | 308.89 | 182.03 | 36.87 | HU11 | 784.35 | HU33 |
| GVA 22 | 545.58 | 527.00 | 311.32 | 59.22 | HU11 | 1 557.26 | PL92 |
| GHG 15 | 0.031 | 0.025 | 0.024 | 0.003 | PL84 | 0.130 | PL42 |
| GHG 22 | 0.032 | 0.026 | 0.026 | 0.004 | PL84 | 0.134 | HU11 |

Source: Own calculations, data obtained from Eurostat for 2015, 2022

Monitoring the achievement of not only performance goals, but also sustainability goals in the dairy sector is possible based on an assessment of the eco-efficiency of this sector. Eco-efficiency reflects the ability to generate greater desirable output from given inputs while reducing undesirable outputs such as greenhouse gas emissions.

The dairy sector’s eco-efficiency scores of V4 regions in 2015 and 2022 are analysed in the second part and are shown in Figure 1.

Figure 1 Eco-efficiency of V4 regional dairy sector in 2015 and 2022



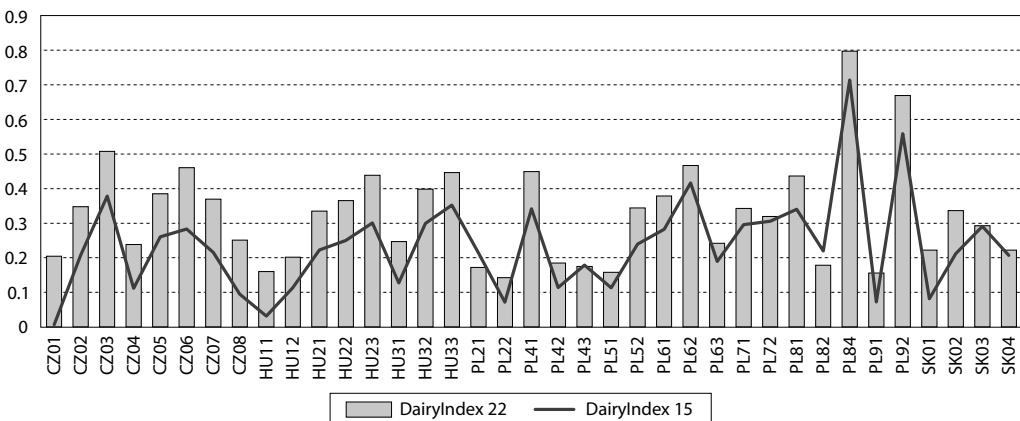
Source: Own calculations, data obtained from Eurostat for 2015, 2022

In 2015, only seven V4 regions achieved eco-efficiency in the dairy sector (ecoTE = 1.0 in Figure 1): These included the capital regions of each V4 country – CZ01: Praha, HU11: Budapest, PL91: Warszawski Stoleczny, and SK01: Bratislavský kraj – along with one other Polish region, PL92:

Mazowiecki regionalny, and two Hungarian regions, HU33: Dél-Alföld, and HU23: Dél-Dunántúl. In 2022, all capital regions and PL92: Mazowiecki regionalny remained eco-efficient. Their strong human capital, infrastructure, research capacity and access to financial and policy support continue to facilitate innovation and adoption of eco-efficient dairy practices. Three additional regions became eco-efficient in 2022 (HU22: Nyugat-Dunántúl, PL22: Śląskie and PL71: Łódzkie). Conversely, the previously eco-efficient Hungarian regions HU33: Dél-Alföld and HU23: Dél-Dunántúl became eco-inefficient. Altogether, eight V4 regions were eco-efficient in 2022. Eco-efficiency declined in most Hungarian regions except Pest HU11: Pest, HU21: Közép-Dunántúl, and HU22: Nyugat-Dunántúl. Several Polish (PL41: Wielkopolskie, PL51: Dolnośląskie, PL6 All other V4 regions were eco-inefficient in both years.3: Pomorskie, PL82: Podkarpackie) and Slovak regions (SK02: Západné Slovensko, and SK04: Východné Slovensko) also recorded decreases, driven by rising input costs, farm structural changes, labour shortages, limited investment capacity, and insufficient environmental incentives.

To complement the eco-efficiency results, regional performance was also assessed through a Dairy Competitiveness Index for 2015 and 2022 (DairyIndex 15 and DairyIndex 22 in Figure 2). The index ranges from 0 to 0.8, and V4 regions were ranked from the most (1st) to the least competitive (37th). In both years, the top four positions were held by the same regions, reflecting their strong and stable role in the V4 dairy production. The most competitive region was the Polish PL84: Podlaskie, supported by the presence of major dairy processors (SM Mlekolpol, SM Mlekovita, SM Piątnica). Second was PL92: Mazowiecki regionalny, also home to leading companies. In 2015, PL62: Warmińsko-Mazurskie ranked third and CZ03: Jihozápad fourth; these two exchanged places by 2022. The Hungarian region HU33: Dél-Alföld ranked fifth in 2015 but dropped to seventh by 2022, while the Czech region CZ06: Jihovýchod improved markedly from 13th to 5th, reflecting its strong processing capacity. Competitiveness improved in most V4 regions between 2015 and 2022. Only three Polish regions (PL82: Podkarpackie, PL21: Małopolskie, and PL43: Lubuskie) – declined substantially due to lower productivity, structural constraints, and rising GHG emissions per unit of milk. In 2015, the least competitive region was CZ01: Praha, but it rose to 28th place by 2022 due to its low initial agricultural base. By contrast, PL22: Śląskie became the least competitive in 2022, largely due to limited dairy production, small farm sizes, and the absence of major processors. Capital-city regions in general (Praha, Budapest, Warsaw, Bratislava) consistently ranked near the bottom, reflecting their predominantly urban and service-oriented economic structure rather than dairy production.

Figure 2 Dairy Competitiveness Index of V4 regions in 2015 and 2022



Source: Own calculations, data obtained from Eurostat for 2015, 2022

To rank the V4 regions based on the achieved eco-efficiency values, the original input-oriented DEA model with the assumption of constant returns to scale is modified to the Super-efficiency DEA model. Based on the super eco-efficiency values, the V4 regions are ranked in Table 2 (SuperTE15 and SuperTE22). To assess the relationship between eco-efficiency and competitiveness, the table also presents the ranking of the V4 regions based on the constructed Dairy Competitiveness Index. The rankings are based on the relative position of each region in the year 2015 and 2022, enabling an assessment of both performance and dynamics over time.

Table 2 Ranking of V4 regions based on super TE and Dairy Competitiveness Index in 2015, 2022

| NUTS2 | superTE15 | superTE22 | Dairy Index15 | Dairy Index22 | NUTS2 | superTE15 | superTE22 | Dairy Index15 | Dairy Index22 |
|-------|-----------|-----------|---------------|---------------|-------|-----------|-----------|---------------|---------------|
| HU11 | 2 | 1 | 36 | 34 | HU31 | 13 | 20 | 27 | 23 |
| CZ01 | 1 | 2 | 37 | 28 | CZ03 | 26 | 21 | 4 | 3 |
| PL91 | 4 | 3 | 34 | 36 | HU33 | 5 | 22 | 5 | 7 |
| PL92 | 3 | 4 | 2 | 2 | HU32 | 9 | 23 | 10 | 10 |
| HU22 | 12 | 5 | 16 | 14 | PL61 | 27 | 24 | 14 | 12 |
| SK01 | 6 | 6 | 33 | 27 | PL42 | 28 | 25 | 28 | 30 |
| PL22 | 11 | 7 | 35 | 37 | SK03 | 36 | 26 | 12 | 21 |
| PL71 | 16 | 8 | 11 | 17 | HU12 | 14 | 27 | 30 | 29 |
| PL72 | 10 | 9 | 8 | 20 | PL43 | 33 | 28 | 26 | 32 |
| PL21 | 8 | 10 | 21 | 33 | PL62 | 29 | 29 | 3 | 4 |
| HU23 | 7 | 11 | 9 | 8 | SK02 | 25 | 30 | 22 | 18 |
| CZ08 | 17 | 12 | 32 | 22 | PL84 | 34 | 31 | 1 | 1 |
| CZ06 | 24 | 13 | 13 | 5 | PL63 | 23 | 32 | 25 | 24 |
| CZ05 | 22 | 14 | 15 | 11 | SK04 | 31 | 33 | 23 | 26 |
| CZ04 | 18 | 15 | 31 | 25 | PL41 | 32 | 34 | 6 | 6 |
| PL81 | 15 | 16 | 7 | 9 | PL82 | 30 | 35 | 19 | 31 |
| CZ07 | 21 | 17 | 20 | 13 | PL52 | 37 | 36 | 17 | 16 |
| HU21 | 19 | 18 | 18 | 19 | PL51 | 35 | 37 | 29 | 35 |
| CZ02 | 20 | 19 | 24 | 15 | | | | | |

Source: Own calculations, data obtained from Eurostat for 2015, 2022

Almost all the most competitive V4 regions in dairy production (PL84: Podlaskie, CZ03: Jihozápad, PL62: Warmińsko-mazurskie, and PL41: Wielkopolskie) ranked relatively low in terms of eco-efficiency, except for PL92: Mazowiecki regionalny. These regions are key dairy producers and prioritize high output levels to meet domestic and export demand. However, achieving high volumes does not necessarily mean that resources (e.g., feed, water, energy) are used efficiently relative to output. While large farms benefit from economies of scale, they can also be less flexible in adopting new eco-friendly technologies if those require significant capital investment or operational change. In contrast, regions with smaller, innovative farms sometimes adopt eco-efficient practices faster. These highly dairy competitive regions could further enhance their competitiveness by improving eco-efficiency and achieving higher outputs from a given level of input. On the other hand, the most eco-efficient regions, such as HU11: Budapest, CZ01: Praha, PL91: Warszawski Stołeczny and SK01: Bratislavský kraj, ranked among the lowest in terms of dairy

competitiveness. This suggests that while eco-efficiency can contribute to better competitiveness, it may not be sufficient in regions where the dairy sector is economically less significant or small in scale. Only Polish region PL92: Mazowiecki regionalny was both eco-efficient and highly competitive. The presence of large, modern dairy farms and processing facilities in this region contributes to higher productivity. This Polish region is located near Warsaw, and, therefore, the region enjoys excellent infrastructure, including transport, logistics, and access to research institutions and extension services. Unlike in many other regions where these two aspects diverge, PL92: Mazowiecki regionalny shows that economic performance and environmental responsibility can align, particularly when supported by smart investment and innovation policies. Hungarian region HU33: Dél-Alföld was highly competitive in both years (6th in 2015 and 8th in 2022) but lost its eco-efficiency status in 2022. This highlights that a region can maintain competitiveness even as eco-efficiency declines, particularly if scale, market access, or economic output remain strong.

The relationship between dairy eco-efficiency levels, based on the super-DEA model, and the Dairy Competitiveness Index was examined using Pearson's correlation coefficient. The coefficient was -0.32 in 2015 and -0.19 in 2022, with p-value above α (0.05) in both analysed years, indicating a very weak and statistically insignificant relationship between these two variables (Table 3).

Table 3 Pearson Correlation Coefficient in 2015 and 2022

| Pearson Correlation Coefficients, N = 37 Prob > r under H0: Rho=0 | |
|--|-------------|
| | TE15 |
| IDC15 | -0.32456 |
| | 0.0500 |
| Pearson Correlation Coefficients, N = 37 Prob > r under H0: Rho=0 | |
| | TE22 |
| IDC22 | -0.19391 |
| | 0.2502 |

Source: Own calculations, data obtained from Eurostat for 2015, 2022

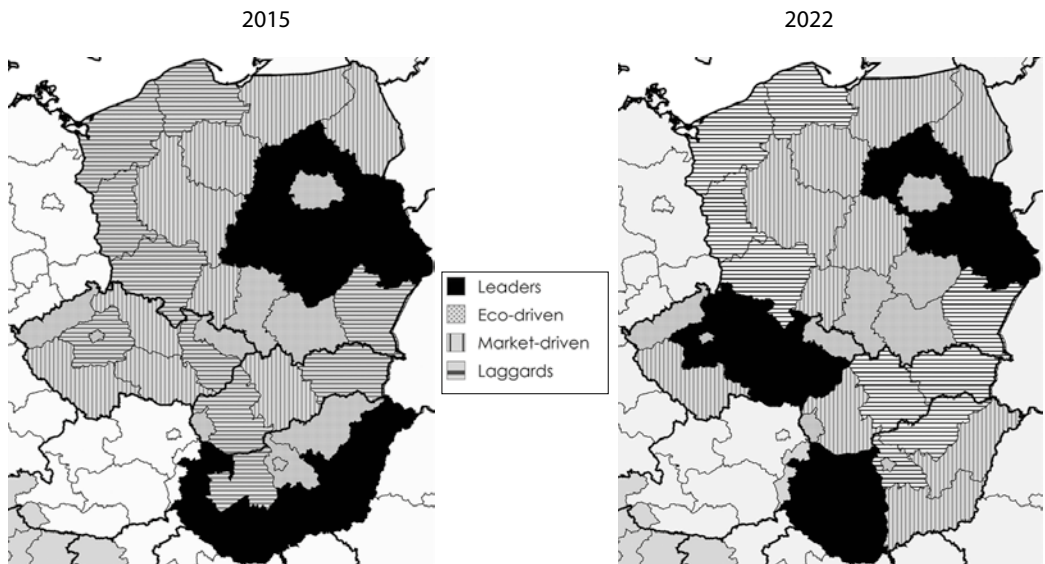
The proposed research hypothesis – *The eco-efficiency of a region ensures a higher level of outputs for given inputs, thereby increasing its competitiveness.* – was rejected because the link between eco-efficiency and competitiveness in the dairy sector was not statistically confirmed.

In both years, based on dairy eco-efficiency values and Dairy Competitiveness Index values, the V4 regions are classified into four groups: Leaders – regions achieving above-average values in both eco-efficiency and the Dairy Competitiveness Index (highlighted in black on the maps), Market-driven regions – regions achieving above-average values in the Dairy Competitiveness Index but below-average values in eco-efficiency (highlighted with checker pattern on the maps), Eco-driven regions – regions achieving above-average eco-efficiency but below-average values in the Dairy Competitiveness Index (highlighted in white on the maps) and Laggards – regions with below-average values in both the Dairy Competitiveness Index and eco-efficiency (highlighted with horizontal stripes on the maps).

In 2015, the Leaders group included eight regions: four Hungarian (HU22: Nyugat-Dunántúl, HU23: Dél-Dunántúl, HU32: Észak-Alföld, and HU33: Dél-Alföld); and four Polish (PL71: Łódzkie, PL72: Świętokrzyskie, PL81: Lubelskie and PL92: Mazowiecki regionalny) (Figure 3). The Market-driven group consisted of nine regions, mainly strong dairy producers from the Czech Republic (CZ03: Jihozápad, CZ05:

Severovýchod and CZ06: Jihovýchod), Poland (PL41: Wielkopolskie, PL52: Opolskie, PL61: Kujawsko-pomorskie, PL62: Warmińsko-mazurskie and PL84: Podlaskie), and Slovakia (SK03: Stredné Slovensko). The Eco-driven group included ten regions, comprising the capital regions CZ01: Praha, HU11: Budapest, PL91: Warszawski stołeczny, and SK01: Bratislavský kraj, as well as other environmentally strong regions: CZ04: Severozápad, CZ08: Moravskoslezsko, HU12: Pest, HU31: Észak-Magyarország, PL21: Małopolskie, and PL22: Śląskie. The Laggards group also included ten regions from all V4 countries, generally those with below-average eco-efficiency and competitiveness, namely: The Czech regions CZ02: Střední Čechy and CZ07: Střední Morava; the Hungarian regions HU21: Közép-Dunántúl; the Polish regions PL42: Zachodniopomorskie, PL43: Lubuskie, PL51: Dolnośląskie, PL63: Pomorskie and PL82: Podkarpackie; and the Slovak regions SK02: Západné Slovensko and SK04: Východné Slovensko (Figure 3).

Figure 3 Map of V4 groups in 2015 and 2022



Source: Own calculations, data obtained from Eurostat for 2015, 2022

By 2022, the Leaders expanded to nine regions (Figure 3): HU22: Nyugat-Dunántúl, HU23: Dél-Dunántúl, PL81: Lubelskie, PL92: Mazowiecki regionalny (maintained); CZ05: Severovýchod, CZ06: Jihovýchod (improved eco-efficiency); HU21: Közép-Dunántúl, CZ02: Střední Čechy, CZ07: Střední Morava (improved both).

The Market-driven group included ten regions: CZ03: Jihozápad, PL41: Wielkopolskie, PL52: Opolskie, PL61: Kujawsko-pomorskie, PL62: Warmińsko-mazurskie, PL84: Podlaskie (maintained); HU3: Észak-Alföld, HU33: Dél-Alföld, PL71: Łódzkie (downgraded from Leaders); SK02: Západné Slovensko (improved competitiveness).

The Eco-driven group included nine regions: CZ01: Praha, CZ04: Severozápad, CZ08: Moravskoslezsko, HU11: Budapest, PL21: Małopolskie, PL22: Śląskie, PL91: Warszawski stołeczny, SK01: Bratislavský kraj (maintained), and PL72 Świętokrzyskie (downgraded from Leaders).

The Laggards group included nine regions: PL42: Zachodniopomorskie, PL43: Lubuskie, PL51: Dolnośląskie, PL63: Pomorskie, PL82: Podkarpackie, SK04: Východné Slovensko (maintained); HU12: Pest, HU31: Észak-Magyarország (downgraded from Eco-driven); SK03: Stredné Slovensko (downgraded from Market-driven).

These classifications highlight persistent disparities in eco-efficiency and competitiveness. Czech regions have improved the most, with several moving into the Leaders by 2022 and no remaining Laggards by 2022. Polish regions largely maintained positions, Hungarian regions stagnated or declined, and Slovak regions remained the weakest. The coexistence of Eco-driven and Market-driven regions in both years shows that eco-efficiency and competitiveness do not necessarily align, confirming limited convergence in the V4 dairy sector and the need for tailored, region-specific strategies.

4 DISCUSSION

Based on the results, except for regions containing a capital city, the remaining eco-efficient regions were from Poland and Hungary. According to Náglová & Rudinskaya (2021) and Žáková Kroupová et al. (2020), Poland had the most efficient dairy sector among the V4 countries. In line with our focus, Rybaczevska-Błazejowska & Masternuk-Janus (2018) argued that ecological efficiency should be analysed within specific agricultural sectors, rather than agriculture. As their analysis suggests, Polish regions PL21: Malopolskie and PL41: Wielkopolskie were overall agriculturally eco-efficient. However, similarly as in this study, they were eco-inefficient in the case of dairy farming, despite having a significant number of cows. They produce relatively less milk due to a combination of factors, including smaller herds, less specialized farming, and potentially less focus on maximizing the milk yield of individual cows.

Consistent with the findings of this study, the Hungarian region HU22: Nyugat-Dunántúl was also recognized as fully efficient by Špička & Smutka (2014) and demonstrated the highest Malmquist index value among the V4 regions in the analysis by Špička & Machek (2015). On the other hand, over time, the eco-efficiency decline was observed in almost all Hungarian regions. According to Századvég (2022), this decline in eco-efficiency can be attributed to a combination of economic, structural, and technological challenges affecting the Hungarian dairy sector. These regions face a significant shortage of labour, especially skilled workers essential for modern dairy operations, which hinders the adoption of efficient practices and advanced technology management. Moreover, rising energy costs have increased operating expenses, making it financially difficult for dairy farms to maintain or improve environmentally efficient practices.

When examining dairy competitiveness, the best positions were achieved predominantly by eco-inefficient Polish regions, except for PL92: Mazowiecki regionalny. Parzonko (2024) and Nagy & Jámber (2019) also recognized Poland as the most competitive V4 country in the dairy sector, thanks to its key dairy regions that prioritize high output levels to meet both domestic and export demand.

Based on the eco-efficiency and competitiveness rankings, as well as the computed Pearson's correlation coefficient, which indicated a very weak and statistically insignificant relationship between eco-efficiency and competitiveness, the research hypothesis was rejected. At the regional level, high environmental performance does not play a key role in supporting economic competitiveness, unlike at the farm level (Liroy et al., 2021). Similarly, Arru et al. (2024) reported that economic performance and environmental outcomes in all livestock subsectors developed in different directions, suggesting that improvements in one do not necessarily translate into gains in the other. From both the ecological and economic standpoint, Czechia recorded the greatest progress between 2015 and 2022. This positive trend reflects successful modernization processes and a gradual movement toward the EU average. Consistent with these findings, Bórawski et al. (2020) also reported that dairy farms in Czechia exhibited the highest level of economic sustainability among the V4 countries.

CONCLUSION

This study provides a multidimensional assessment of the dairy sector in the Visegrad four (V4) regions, analysing its economic output, environmental performance, eco-efficiency and competitiveness over the period 2015 and 2022.

Overall, milk production per cow and agricultural gross value added in € per capita increased in all V4 countries, reflecting improvements in productivity and economic performance. However, this growth was uneven across regions, with some Hungarian and Polish regions even experiencing a decline. Rising standard deviations for both indicators suggest a widening gap between high-performing and lagging regions, particularly in Hungary and Poland. Overall agricultural greenhouse gas emissions in the V4 also increased slightly, mainly driven by most Hungarian and Polish regions, where larger and more intensive livestock production, combined with more production-oriented agricultural policies, contributed to the rise. These trends highlight the importance of promoting balanced regional development and environmentally sustainable practices in the V4 dairy sector.

The eco-efficiency analysis further revealed that while some regions improved between 2015 and 2022, others, such as almost all Hungarian regions, four Polish regions, and two Slovak regions, experienced a decline. Structural challenges – including labour shortages, rising production costs, and limited technological adoption – have eroded environmental performance in several areas. In 2015, all capital regions of the V4 countries, along with the Polish region PL92: Mazowiecki regionalny and two Hungarian regions HU33: Dél-Alföld and HU23: Dél-Dunántúl, had eco-efficient dairy sectors (a total of seven V4 regions). By 2022, this number increased to eight. Each of the capital regions, as well as PL92: Mazowiecki regionalny near Warsaw, maintained their eco-efficiency. These regions benefit from well-developed infrastructure, including transport, logistics, and access to research institutions and advisory services. Additionally, the Hungarian region HU22: Nyugat-Dunántúl and the Polish regions PL22: Śląskie and PL71: Łódzkie improved their eco-efficiency and became eco-efficient by 2022. Excluding the capital regions, most eco-efficient dairy regions in 2022 were in Poland.

The Dairy Competitiveness Index adds another layer of insight. The most competitive regions remained consistent over time. In both years examined, the top four positions were maintained by the same V4 regions. The most competitive dairy sector among the V4 regions had the Polish region PL84: Podlaskie, home to three leading Polish dairy companies. In 2015, the second position was held by another Polish region, PL92: Mazowiecki regionalny, followed by PL62: Warmińsko-Mazurskie in third place and the Czech region CZ03: Jihozápad in fourth. In 2022, the latter two regions swapped positions, with PL62: Warmińsko-Mazurskie taking fourth and CZ03: Jihozápad moving up to third place. All mentioned regions host major dairy companies and exhibit strong production capacity and market orientation. Conversely, capital city regions, which had eco-efficient dairy sector, ranked among the least competitive due to the relatively low scale and economic relevance of dairy production in urban settings.

A notable finding is the very weak connection between eco-efficiency and competitiveness. Based on computed Pearson's correlation coefficient, the proposed research hypothesis – *The eco-efficiency of a region ensures a higher level of outputs for given inputs, thereby increasing its competitiveness.* – was rejected.

Some regions perform well environmentally but lag in market competitiveness, and vice versa. For example, HU11: Budapest, CZ01: Praha, PL91: Warszawski Stołeczny, and SK01: Bratislavský kraj were the most eco-efficient in 2022 but among the least competitive. Conversely, key dairy-producing regions prioritizing high output often ranked low in eco-efficiency, highlighting that strong environmental performance does not guarantee market success, nor does competitiveness ensure sustainability. This underscores the need for integrated strategies addressing productivity, market strength, and eco-efficiency simultaneously.

The classification of V4 regions into Leaders, Market-driven, Eco-driven, and Laggards revealed persistent structural disparities:

1. Czechia improved most significantly. Four regions moved up: two from Market-driven to Leaders via improved eco-efficiency, and two from Laggards to Leaders via gains in both eco-efficiency and competitiveness. By 2022, no Czech region remained in the Laggards, reflecting structural modernization and convergence with the EU average.

2. Poland largely maintained positions, with minor shifts: one region dropped from Leaders to Market-driven, and another from Leaders to Eco-driven.
3. Hungary saw several regions decline, moving from Leaders to Market-driven or from Eco-driven to Laggards, due to declining milk yields, rising GHG emissions, aging farm infrastructure, and slower adoption of low-emission technologies. Only HU21 Közép-Dunántúl improved into the Leaders.
4. Slovakia remained the weakest performer, with no regions in Leaders and most in Laggards. Only minor improvements were observed (e.g., SK02 Západné Slovensko moving to Market-driven).

The coexistence of Eco-driven and Market-driven groups in both years confirms that eco-efficiency and competitiveness do not automatically align. Regions face different combinations of environmental and economic challenges, requiring differentiated policy interventions: Eco-driven regions need support to boost productivity; Market-driven regions require investment in environmental technologies; Laggards need comprehensive support; Leaders can act as hubs for knowledge transfer and innovation.

These findings align closely with the CAP 2023–2027, especially eco-schemes aiming to reduce environmental pressures while maintaining productivity. Measures such as precision nutrient management, improved grassland practices, low-emission livestock strategies, and enhanced animal welfare can help regions reduce GHG emissions and improve eco-efficiency without compromising output. Eco-driven but less competitive regions can benefit from incentives for sustainable practices, while high output but environmentally weaker regions require measures to reduce emissions intensity. Overall, the CAP framework is well-suited to address structural disparities and promote climate-smart innovations in the V4 dairy sector.

The study is limited using regional-level data, which may mask farm-level heterogeneity in productivity, technology adoption, and environmental performance. Only a limited set of inputs and outputs was included, focusing on milk production, agricultural GVA, and GHG emissions, which may not capture all dimensions of eco-efficiency and competitiveness. The DEA model assumes constant returns to scale and considers only GHG as an undesirable output, potentially oversimplifying production realities and environmental impacts. Finally, the analysis compares only two years (2015 and 2022), limiting the ability to observe longer-term trends or causal relationships. Future research could address these limitations by incorporating farm-level data, additional environmental and economic indicators, and longer time series to better understand the drivers of eco-efficiency and competitiveness.

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