
ASSESSING EU AGRICULTURAL PERFORMANCE TOWARD A CIRCULAR ECONOMY: EVIDENCE FROM CLUSTER ANALYSIS

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ARTICLE INFO

Original Article

Received: 19 September 2025

Accepted: 20 October 2025

doi:10.59267/ekoPolj2603719R

UDC 338.43.02:330.341.1]
:303.725.32(4-672EU)

Keywords:

*agriculture, performance,
circular economy, cluster
analysis, resilience*

JEL: Q10, Q19, Q57

ABSTRACT

The purpose of this paper is to evaluate the structural performance of European agriculture in the context of the circular economy transition. The methodology applies a two-step cluster analysis to three indicators: AgroBioDiversity Index, Livestock Density Index, and Farms by Economic Size, using Eurostat data. The results identify five agricultural models, ranging from extensive small-scale systems with high biodiversity and weak economic strength, to industrialized structures with large farms and strong economic capacity, but greater sustainability risks. Findings show one-size-fits-all policy is ineffective. The recommendations emphasize the need for differentiated policies that enhance the resilience of extensive systems, mitigate environmental pressures in industrial systems, and maintain balance in mixed models. The study provides additional empirical evidence for tailoring circular economy strategies to diverse agricultural structures across the European Union, supporting context-specific approaches to sustainable agriculture.

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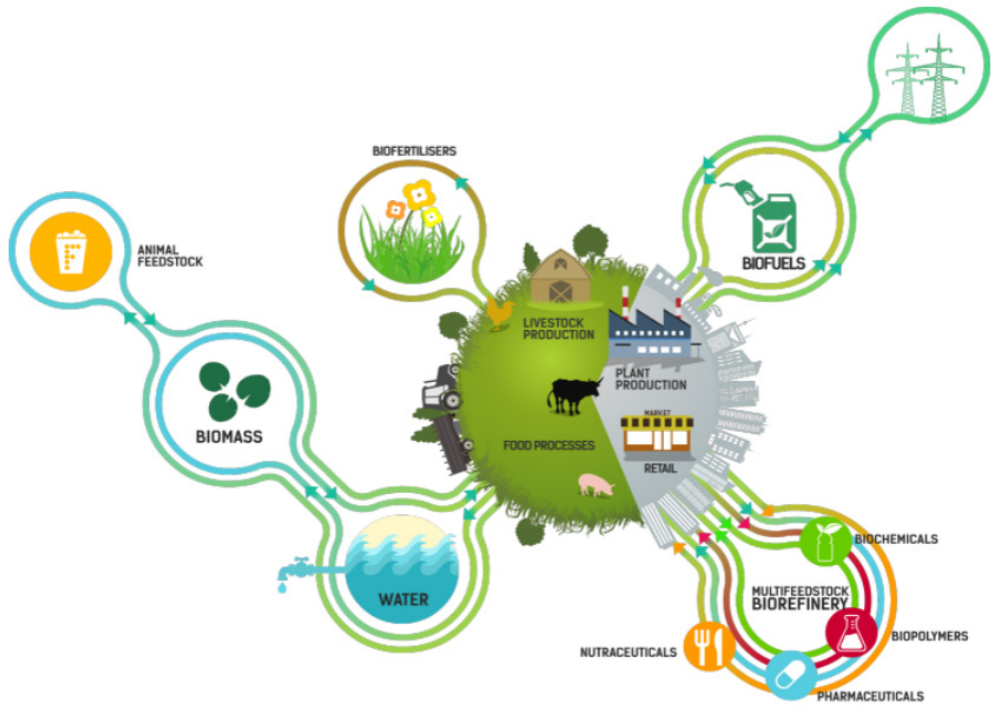
Introduction

The transformation of agricultural systems is central to achieving the objectives of the European Green Deal and the 2030 Agenda for Sustainable Development. Agriculture simultaneously drives economic growth, rural employment, and food security, but it also generates substantial environmental pressures, including land degradation, biodiversity loss, and greenhouse gas emissions (European Commission, 2019). In this context, the concept of the circular economy (CE) has emerged as a guiding framework for restructuring agri-food systems toward resource efficiency, closed nutrient loops, and enhanced ecological resilience (Geissdoerfer et al., 2017; Jurgilevich et al., 2016).

A growing body of literature emphasizes the role of indicators in monitoring sustainability and CE transitions in agriculture. Silvestri et al. (2024) stress that integrated sets of indicators are essential to capture the triple bottom line of environmental, social, and economic performance. Velasco-Muñoz et al. (2021) propose adapting CE strategies specifically to agricultural systems, highlighting the importance of narrowing, slowing, and closing resource loops through regenerative practices. Similarly, Castillo-Díaz et al. (2023) demonstrate that composite indicators can be used to benchmark the sustainability of agri-food systems at the EU level. Despite these advances, empirical studies that segment agricultural structures based on performance indicators remain limited, particularly in linking biodiversity, production intensity, and economic capacity to CE pathways.

This paper addresses that gap by assessing EU agricultural performance through three core indicators: the AgroBioDiversity Index (AGBDI), the Livestock Density Index (LDI), and Farms by Economic Size (FES). These dimensions are particularly relevant to CE transitions: agrobiodiversity supports ecological stability and resilience; livestock density reflects resource intensity and environmental pressures; and farm economic size indicates the economic viability and capacity for innovation (Figure 1). By applying a two-step cluster analysis, this study identifies structural models of agriculture across the EU and interprets their implications for sustainable development and CE-aligned policy design.

This study's originality lies in combining three structural indicators into an EU-wide segmentation using two-step cluster analysis. Whereas prior work benchmarks sustainability through composite indices (Castillo-Díaz et al., 2023) or maps spatial diversification (Matysik-Pejas et al., 2023), our typology uncovers distinct structural models and links each to tailored CE measures.

Figure 1. Connection between CE and agrobiodiversity

Source: Authors' adaptation according to AgroCycle

The central research question is: How do biodiversity, livestock intensity, and economic farm size combine to structure EU agriculture, and what does this imply for tailored circular economy strategies? The aim is to provide a data-driven classification of EU agricultural systems that supports differentiated policy strategies using agricultural predictive data processing. Rather than promoting uniform measures, the analysis offers evidence for tailoring CE-oriented interventions to the specific conditions of each cluster, balancing ecological and economic objectives across Europe.

European Agriculture and the CE Transition: Literature Review

The transition of European agriculture toward a CE is a rapidly evolving research area, reflecting the sector's central role in sustainability, resource efficiency, and climate goals. It is gaining increasing attention as a framework for achieving sustainable food systems, improving biodiversity, and minimizing environmental externalities. The literature highlights both the promise and complexity of this transformation.

Circular agriculture aims to minimize inputs and waste by closing resource loops, thereby reducing environmental impact. It promotes the reuse, recycling, and regeneration of resources within the agricultural and food system. Key principles include nutrient recycling, agrobiodiversity, reduced livestock intensity, and integrated production

systems (Chung et al., 2024; Kotyal, 2023). This model stands in contrast to the traditional linear systems, which are resource-intensive and environmentally damaging. It represents a shift from linear “take-make-dispose” models to systems that prioritize resource reuse, waste minimization, and environmental regeneration. European policy frameworks, such as the Circular Economy Action Plan and the European Green Deal, have established CE as a strategic priority; however, regulatory instruments specific to agriculture remain underdeveloped, and implementation is uneven across member states (Georgescu et al., 2025). Tailored, region-specific policies and investments in infrastructure are seen as essential for effective CE adoption (Zarbà et al., 2021).

European agriculture is highly heterogeneous, with significant spatial and structural differences that influence the implementation of CE. Studies highlight that circular models require differentiated implementation strategies based on these structural differences (Dovgal et al., 2024). For example, regions with small, biodiverse farms may be better aligned with CE principles but lack economic scalability, while industrialized systems present efficiency but risk environmental degradation. Countries with advanced agricultural sectors tend to be further along in adopting CE principles, while less developed regions face greater barriers due to limited infrastructure, investment, and institutional support (Matysik-Pejas et al., 2023; Georgescu et al., 2025). Cluster analyses and composite indicators reveal that balanced systems, those combining biodiversity, moderate livestock intensity, and medium farm size, are most closely aligned with sustainable CE outcomes (Matysik-Pejas et al., 2023; Castillo-Díaz et al., 2023).

The literature identifies several core strategies for advancing CE in agriculture. Waste recovery and bioenergy have been prominent, particularly anaerobic digestion and biogas production, though their success depends on feedstock quality, infrastructure, and innovative business models (Barros et al., 2020; Haque et al., 2023). Resource efficiency and recycling, including reducing raw material use, remain the most widely adopted CE strategies, especially in the food and beverage sector (De Pascale et al., 2023). Local productive systems, emphasizing territorial balance and regional supply chains, are highlighted as means to enhance resilience and sustainability (Castillo-Díaz et al., 2023).

Several challenges hinder CE adoption. Technological and economic barriers, including high costs, inadequate infrastructure, and limited life cycle assessment data, hinder implementation (Velasco-Muñoz et al., 2021; Haque et al., 2023). Stakeholder engagement is another critical factor, as CE requires collaboration among farmers, policymakers, and consumers, with government incentives playing a decisive role (Muscio & Sisto, 2020; Haque et al., 2023; Rađenović et al., 2025). Research and innovation gaps also persist; while publications on CE in agriculture have increased since 2015, economic and social dimensions remain underexplored compared to environmental impacts (Ali & Ali, 2024; Silvestri et al., 2024).

Adopting CE principles in European agriculture can reduce land use and greenhouse gas emissions, enhance food security, and support employment, including narrowing

gender gaps in agricultural work (van Zanten et al., 2023). However, trade-offs exist, as economic and social progress may sometimes come at the expense of environmental quality, underscoring the need for integrated policy approaches (Castillo-Díaz et al., 2023; van Zanten et al., 2023).

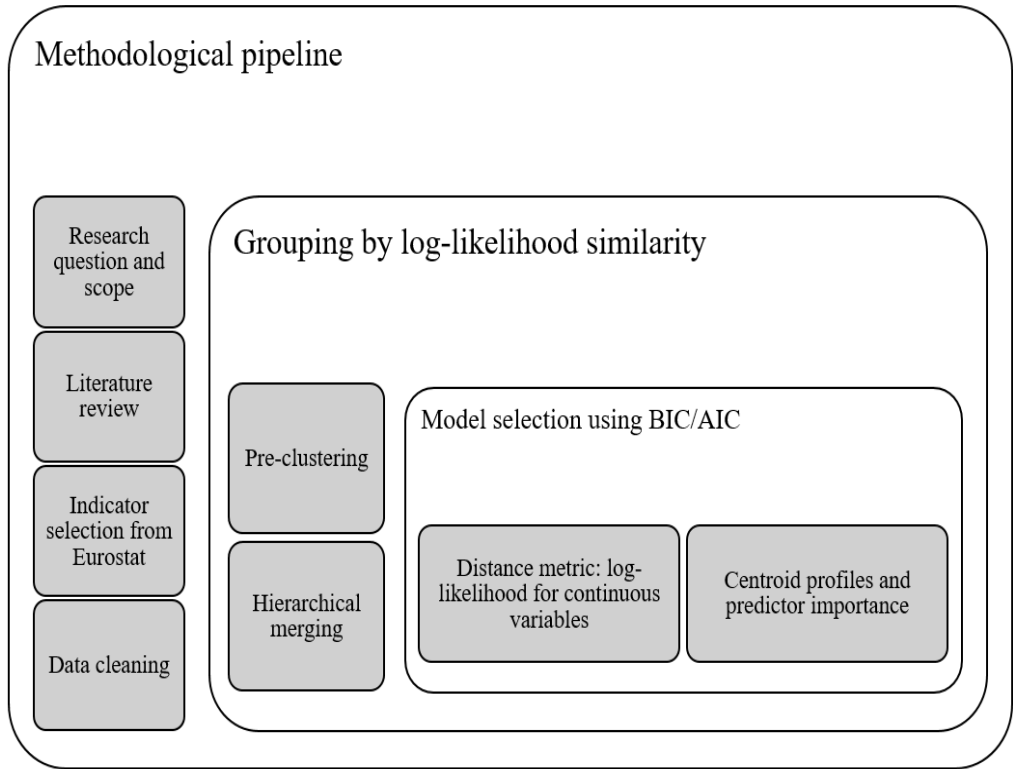
The literature underscores that while the transition to CE in European agriculture holds significant promise for sustainability, it is shaped by structural diversity, policy gaps, and the need for integrated, context-specific strategies. Further research and innovation, especially in economic and social dimensions, are critical for advancing this transition.

Materials and methods

The analysis is based on the application of the two-step cluster method to categorize EU countries according to their structural characteristics in agriculture. The two-step cluster analysis is a hybrid clustering technique designed to efficiently handle large datasets with mixed-type variables (both continuous and categorical) (Rađenović & Rajić, 2025). Unlike traditional clustering procedures, such as k-means (which requires only continuous variables) or hierarchical clustering (which can become computationally demanding with larger sample sizes), the two-step method combines the advantages of both approaches, offering a more robust and scalable solution (Ahmed et al., 2020). The procedure is carried out in two main phases, as illustrated in the methodological pipeline (Figure 2). In the first step (pre-clustering), cases are scanned sequentially and assigned into small “sub-clusters” using a distance measure. For continuous variables, the algorithm utilizes the log-likelihood distance, which assesses the similarity of observations based on their probability distributions rather than absolute distances. For categorical variables, a frequency-based approach is applied. In the second step, the sub-clusters are grouped into the final clusters using an agglomerative hierarchical method, which merges them iteratively until an optimal cluster solution is reached. A key strength of the two-step procedure is its ability to determine the optimal number of clusters automatically. This is achieved by employing model-fit criteria such as the Bayesian Information Criterion (BIC) or the Akaike Information Criterion (AIC), which balance model complexity with explanatory power (Rađenović & Rajić, 2025). The solution with the lowest BIC or AIC value is selected, thereby avoiding arbitrary pre-specification of the number of clusters. The clustering was performed using three indicators from the EUROSTAT database, according to the last available data for the analysed period of time, 2019-2023, for selected EU members:

- AGBDI (AgroBioDiversity Index) – measures the diversity of agricultural production and the level of agrobiodiversity conservation (Eurostat, 2019),
- LDI (Livestock Density Index) – reflects the intensity of livestock production through animal density per hectare of agricultural land (Eurostat, 2020),
- FES (Farms by Economic Size) – indicates the economic strength of farms measured by the standard output value (Eurostat, 2023).

Figure 2. Methodological pipeline of applied statistical techniques



Source: Authors' visualization

From a statistical standpoint, the two-step cluster method is particularly well suited for studies like this one, where indicators such as the AGBDI, LDI, and FES represent continuous variables with very different ranges and distributions. Before clustering, these variables were standardized to ensure comparability, preventing variables with larger scales (e.g., FES values) from dominating the analysis. The resulting clusters were evaluated using centroid values (means) for each variable, which serve as interpretable profiles of the agricultural systems. Despite these strengths, the two-step cluster analysis also presents certain limitations that must be acknowledged. First, the technique is sensitive to outliers, which can disproportionately influence centroid values and alter cluster boundaries. Second, the method relies on distributional assumptions embedded in the log-likelihood measure. Finally, two-step clustering is less flexible than model-based clustering approaches, which can incorporate prior theoretical knowledge into the classification process (Rađenović & Rajić, 2025).

Results and Discussion

The centroid values of the clusters reveal apparent structural differences across EU agricultural systems (Table 1).

Table 1. Cluster centroids and dispersion

Centroids							
		AGBDI		LDI		FES	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Cluster	1	48.400	4.827	2.636	.746	166.238	206.337
	2	58.285	1.976	1.012	.409	12.818	10.492
	3	56.250	1.500	.302	.089	22.932	23.369
	4	61.150	4.255	.675	.239	49.6663	19.5535
	5	61.666	3.511	.506	.213	231.886	42.214

Source: Authors' calculations

The analysis covered 19 EU member states for which data on agrobiodiversity, livestock density, and farm economic size were jointly available and harmonized. Eight member states (Portugal, Spain, Poland, Romania, Slovakia, Slovenia, Sweden, and the Netherlands) were excluded due to missing or non-comparable values in one or more indicators. This ensures consistency of the dataset and comparability of cluster results across countries.

Cluster 1 (18.5%), which comprises Malta, Ireland, Belgium, and Austria, is defined by an average AGBDI of approximately 48, an LDI of 2.63, and an FES value of 166. This combination indicates low agrobiodiversity, very high livestock density, and relatively large farm sizes, a profile characteristic of intensive livestock-oriented agriculture with strong economic capacity where emphasis is placed on productivity rather than ecological diversity.

The second-largest group, Cluster 2 (25.9%) gathers Lithuania, Estonia, Czechia, and Cyprus, displays an AGBDI of around 58, an LDI of 1.01, and a remarkably low FES of 13. These figures suggest a structure dominated by small farms, low livestock intensity, and medium to high levels of biodiversity, indicating extensive small-scale farming systems which tends to be more economically vulnerable but plays a crucial role in maintaining local biodiversity.

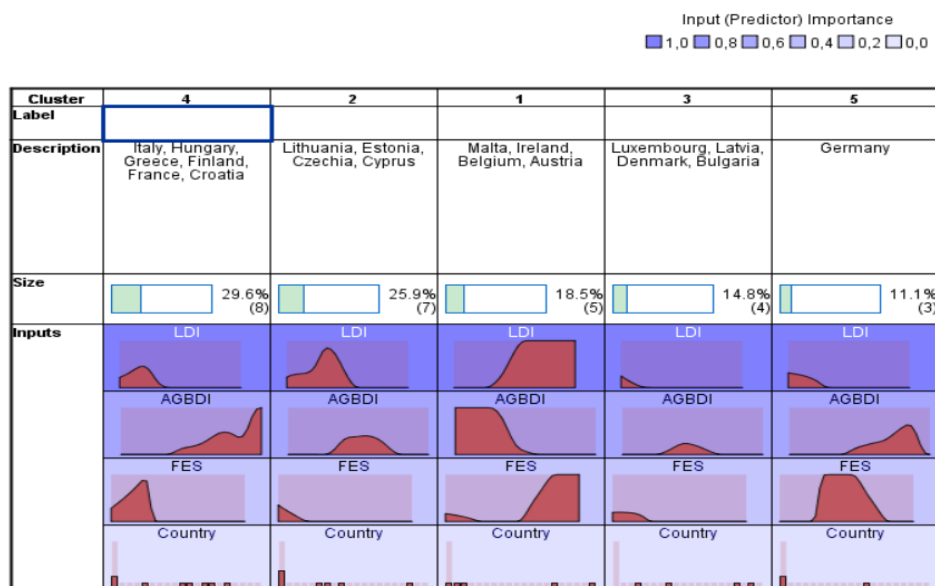
Cluster 3 (14.8%), comprising of Luxembourg, Latvia, Denmark, and Bulgaria, shows centroid values of AGBDI ≈ 56 , LDI ≈ 0.30 , and FES ≈ 23 . These results indicate moderate agrobiodiversity, very low livestock density, and small to medium farm sizes. The combination defines a model of highly extensive agriculture with limited livestock activity, reflecting production systems that are ecologically less intensive, but also economically constrained.

The largest group, Cluster 4 (29.6%), consisting of Italy, Hungary, Greece, Finland, France, and Croatia, records the highest agrobiodiversity (AGBDI ≈ 61), paired with low to medium livestock density (LDI ≈ 0.67) and medium-sized farms (FES ≈ 50). This

profile highlights a balanced agricultural structure, in which ecological and economic dimensions are relatively well harmonized, providing a potential model for sustainable agricultural development within the EU.

Finally, Cluster 5 (11.1%), represented solely by Germany, stands apart with centroid values of AGBDI ≈ 62 , LDI ≈ 0.51 , and FES ≈ 232 . The combination of high biodiversity, low livestock density, and considerable farm size places this cluster at the industrial end of the spectrum. It represents a capital-intensive agricultural model, where scale and economic strength dominate, but where potential risks for biodiversity and long-term sustainability are particularly pronounced.

Figure 3. Cluster characteristics and structure



Source: Authors' calculations

The application of the two-step cluster analysis highlights the structural differentiation of European agriculture (Figure 3). Clusters 2 and 3 represent extensive agricultural systems, characterized by small farm size, low livestock density, and relatively higher biodiversity. These systems face the challenge of increasing productivity while maintaining ecological resilience. Cluster 4 reflects a balanced model where biodiversity, livestock activity, and economic size are harmonized. This type of agriculture is most closely aligned with the concept of sustainability and can serve as a reference model for EU agricultural policies. Clusters 1 and 5 are characterized by high economic capacity, but also carry different risks. Cluster 1 exhibits a firm reliance on intensive livestock farming, whereas Cluster 5 represents industrial agriculture characterized by vast farms, which raises concerns about environmental impacts and biodiversity loss.

The two-step cluster analysis thus provides a nuanced framework for designing

agricultural policies. Instead of uniform policies for all EU countries, it allows for differentiated strategies tailored to the specific conditions of each cluster (Rađenović et al., 2022). The cluster relationship chart (Figure 3) provides a detailed profile of the five agricultural clusters identified through the two-step analysis, showing both the distribution of countries and the relative importance of the input indicators.

The comparison with previous studies supports and refines these findings. Similar patterns of structural heterogeneity across European agriculture are noted in composite sustainability assessments and spatial diversification analyses. For instance, the balanced model observed here mirrors the “territorially balanced” structures linked to stronger sustainability outcomes in Castillo-Díaz et al. (2023). However, unlike studies relying on aggregate sustainability scores, our cluster approach reveals structural typologies, providing more tangible entry points for CE policy design.

The extensive small-scale clusters (2 and 3) confirm results from Matysik-Pejas et al. (2023), who found that smaller, biodiverse farms achieve strong ecological performance but struggle economically. Our results reinforce that without targeted interventions, these systems risk “ecological poverty traps.” Circular strategies such as cooperative processing, shared machinery, and bio-based product valorisation could strengthen viability while maintaining biodiversity (Silvestri et al., 2024; Zarbà et al., 2021).

The intensive livestock-oriented Cluster 1 aligns with previous analyses of nutrient overload and environmental pressure in high-density livestock systems (Velasco-Muñoz et al., 2021). Technologies like manure treatment, biogas production, and precision feeding (Barros et al., 2020) are recognized as key CE levers, while our analysis helps identify the structural context where these interventions yield the highest environmental return.

Similarly, the industrial Cluster 5 confirms findings in van Zanten et al. (2023), who highlight the trade-off between efficiency and ecological stability at scale. While industrial models can contribute to circular goals through economies of scope and resource recovery, our results underscore that maintaining biodiversity and minimizing nutrient leakage require embedded circular design, like industrial symbiosis, renewable energy integration, and closed nutrient and water loops.

Methodologically, our approach diverges from prior index-based or regional typologies (Castillo-Díaz et al., 2023; Matysik-Pejas et al., 2023) by clustering structural indicators, biodiversity, livestock density, and economic size, via a two-step algorithm capable of capturing non-linear interdependencies. This aligns with Silvestri et al. (2024), who argue that multidimensional indicator packs better reflect agricultural performance than single composite indices. The resulting typology operationalizes the strategic view proposed by Velasco-Muñoz et al. (2021), that CE transitions in agriculture must be tailored to the structural realities of different farming systems rather than imposed uniformly.

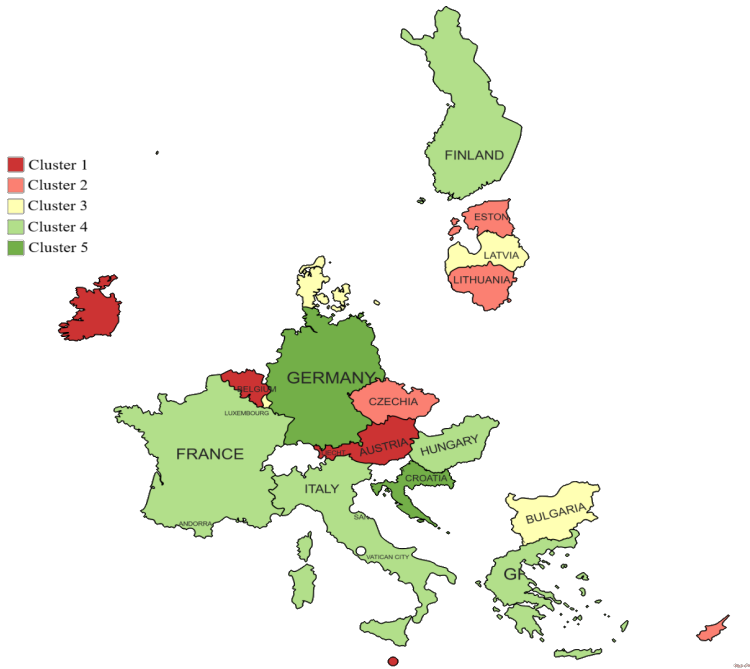
In policy terms, our results are consistent with the European Green Deal's call for resource efficiency and ecological resilience (European Commission, 2019), yet they emphasize the need for cluster-specific implementation. By distinguishing extensive, balanced, intensive, and industrial structures, this study offers an evidence-based framework for adapting Common Agricultural Policy (CAP) eco-schemes and rural development programs to each system's circular potential: supporting cooperative bioeconomy models in extensive clusters, nutrient and waste recycling technologies in intensive systems, and maintaining biodiversity-productivity synergies in balanced contexts.

The results indicate that EU countries can be grouped into distinct agricultural development models depending on the balance between farm economic size, livestock intensity, and agrobiodiversity.

- For capital-intensive systems (Cluster 1), CE interventions should focus on precision feeding, compost processing and biogas, and nutrient recycling as mitigation levers.
- For extensive systems (Clusters 2 and 3), the policy priority should be to strengthen the economic viability of farms while preserving biodiversity.
- For industrial systems (Cluster 5), focus should be placed on environmental protection measures and controlling the negative externalities of over-concentration.
- For balanced systems (Cluster 4), the task is to maintain their equilibrium and promote them as reference models of sustainable agriculture.

This analysis confirms that the development of sustainable agriculture in the EU is a multifaceted process, requiring policies that strike a balance between economic competitiveness and ecological resilience across differentiated agricultural clusters.

Moreover, structural differentiation allows the results to be interpreted through the lens of the CE transition depicted on the European clusters' map (Figure 4). Clusters 2 and 3, dominated by small and extensive systems, align with CE principles of biodiversity preservation and low ecological pressure but face challenges in economic viability. For these systems, circular strategies such as cooperative resource sharing, valorisation of agricultural residues, and integration into local bioeconomy initiatives could strengthen resilience without compromising ecological benefits (Velasco-Muñoz et al., 2021; Zarbà et al., 2021). In contrast, Cluster 4 illustrates a balanced structure where environmental and economic dimensions are already harmonized. This cluster can be considered a reference model for CE-oriented agriculture, demonstrating how moderate livestock intensity and medium-sized farms can support both competitiveness and biodiversity outcomes (Castillo-Díaz et al., 2023).

Figure 4. European clusters' map according to the given results

Source: Authors' visualisation

Clusters 1 and 5, by comparison, illustrate the risks of divergence from CE principles. Cluster 1's intensive livestock orientation raises concerns about nutrient overload, greenhouse gas emissions, and pressure on biodiversity. CE strategies in this context should emphasize nutrient recycling, precision livestock systems, and the integration of renewable energy to mitigate environmental impacts (Barros et al., 2020; Haque et al., 2023). Cluster 5, represented solely by Germany, demonstrates the economic strength of large-scale farming but also the need for industrial symbiosis and closed-loop nutrient and water systems to prevent long-term sustainability risks (van Zanten et al., 2023). Together, these results suggest that CE pathways in agriculture must be cluster-specific, reinforcing biodiversity in extensive systems, maintaining balance in mixed systems, and applying circular innovations to industrialized models.

Conclusions

This study applied a two-step cluster analysis to assess the structural performance of European agriculture using three indicators: agrobiodiversity, livestock density, and farm economic size. The results identified five distinct agricultural models, ranging from extensive small-scale systems with high biodiversity but weak economic strength, to capital-intensive industrial structures with large farms and high economic capacity but greater sustainability risks. Between these extremes, a balanced cluster emerged that combines biodiversity conservation, moderate livestock intensity, and medium-

sized farms, offering the closest alignment with sustainable and circular agriculture. Cross-country contrasts reinforce that similar cluster membership does not imply identical policy levers. For instance, Finland vs Greece (both Cluster 4) share a “balanced” profile statistically, yet differ in climate, soils, and farm structures. So, biodiversity actions (e.g., semi-natural habitat management, pesticide risk reduction) will look quite different in practice. Within Cluster 3, Denmark’s high LDI calls for precision nutrient management and manure processing, whereas Latvia/Bulgaria benefit more from boosting farm viability and habitat connectivity. In Cluster 1, Ireland and Belgium face similar nutrient and grassland pressures but start from different baseline governance and market contexts, implying different policy instruments (e.g., trading schemes vs. investment supports). The findings confirm that the transition of European agriculture toward a CE cannot be achieved through uniform policy measures. Instead, differentiated strategies are required. For extensive systems, the priority is to enhance economic resilience through cooperative models, residue valorisation, and integration into local bioeconomy networks. For industrialized systems, policies should focus on nutrient recycling, precision technologies, and industrial symbiosis to mitigate ecological pressures. Balanced systems should be promoted as reference models, demonstrating how environmental stability and economic competitiveness can be mutually reinforcing.

From a policy perspective, the results provide empirical evidence to guide the design of CE pathways tailored to diverse agricultural contexts within the EU. Incorporating CE strategies into the Common Agricultural Policy and national rural development programs will be essential to support transitions that are both ecologically resilient and economically viable. Future work should address several limitations of this study while deepening cross-country insights. First, our evidence relies on the latest available snapshots, which limit causal interpretation and mask regional heterogeneity, whereas a harmonized multi-year panel would allow for tests of cluster stability and transitions. Future research should expand the indicator set to include environmental footprints, resource circularity metrics, and social dimensions, thereby offering a more comprehensive assessment of how European agriculture can contribute to the broader sustainability and CE agenda.

Acknowledgements

This paper is part of the research supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia pursuant to the agreement No. 451-03-137/2025-03/200148, and contributes to SDGs 12 and 13. In addition, this paper is also part of the research financed by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia, as agreed in decision No. 451-03-136/2025-03/200371.

Conflict of interest

The authors declare no conflict of interest.

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