

Article

Uneven Transitions Toward Circular Agriculture in the EU: Regulatory Drivers, Structural Barriers, and the Role of Policy Implementation Heterogeneity

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Abstract

The present paper analyses the extent to which European Union regulatory frameworks induce the development of circular agriculture within the European Union. In order to evaluate the progress towards circular agriculture within the European Union, a composite Agricultural Circularity Index (ACI) was developed for all EU-27 Member States for the period of 2014–2023. An expert interview and a TOPSIS multi-criteria decision-making technique were employed for the construction of the ACI. Results indicate only marginal improvements in the development of circular agriculture on the aggregate EU level, although a pronounced cross-country divergence towards achieving circularity in agriculture was observed. The following four distinct trajectories in the evolution of the circular economy within the EU were distinguished: structurally advancing promoters, short-term breakthrough cases, high baseline, but eroding systems, and mixed or stagnating countries. Indicator decomposition analysis reveals that durable circularity gains in agriculture arise when increased material recirculation coincides with verifiable bandwidth, whereas intensifying input use frequently negates the progress. The findings underscore that regulatory ambition alone is insufficient: implementation design, uncompromised enforcement, and market integration determine whether initial initiatives towards circular agriculture materialize into sustainable practices or remain transitory. From a policy perspective, the ACI functions as a diagnostic tool to locate structural bottlenecks and to target CAP-style interventions where circular flows can be scaled most effectively.

Keywords: circular agriculture; European Union; TOPSIS



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1. Introduction

The transition toward circular economy has become one of the pivotal goals of the European Union in pursuing its carbon neutrality strategy, which aims to decouple Europe's economic performance from the resource depletion while minimizing waste, emissions, and external input dependence in production systems [1]. Agriculture is considered to be one of the most resource-intensive sectors of the EU economy [2]. This positions agriculture at the focal point in the European green transition, burdening agriculture with a substantial quota of carbon emission reduction [3]. All main EU agricultural steering mechanisms, such as the Circular Economy Action Plan, the Farm-to-Fork Strategy, the European Green Deal, and the reformed Common Agricultural Policy (CAP), were adjusted to address climate goals by promoting circularity in agriculture through nutrient recycling, bio-based value

chains, sustainable land management, and waste minimization [4]. The abovementioned legal instruments help to create the multifaceted incentivization system promoting circular agriculture within the EU through precision agriculture, manure valorization, reduced input (especially fertilizers) intensity, and the expansion of organic agriculture [5].

Despite the strong strategic direction provided by the European Commission, the practical evolution of circular agriculture across EU Member States is remarkably uneven [6]. It is noted that identical EU-level rules can produce nearly contrasting behavioural and environmental responses on a farm level across different countries, depending on unique Member State policy choices [7], inherited agricultural structure [8], value-chain organization [9], and, very importantly, the enforcement intensity of the EU regulation [10].

The abovementioned dynamics raise a research question as follows: to what extent are EU agricultural sectors becoming circular, and does the EU regulation truly boost the adoption of circular practices in the EU agriculture? Existing scientific policy evaluations often examine single instruments or rely on qualitative assessments, leaving a gap in comparative quantitative measurement covering all EU Member States. In order to address this scientific vacuum, the present study develops and applies a novel composite Agricultural Circularity Index (ACI), covering 2014–2023 for EU-27 Member States. Employing a TOPSIS multicriteria method and using expert-validated criteria weighting, the ACI enables a multifaceted evaluation of the progress of the EU Member States towards circularity in agriculture and identifies which structural and institutional determinants translate regulatory intent into real change at a farm level.

The contribution of the present study is twofold: first, it provides a transparent evaluation of the development of the circular practices in agriculture in the EU, based on the quantitative assessments and taking into account both constraining and enabling factors. Secondly, it demonstrates how diverse trajectories in the development of the circular agriculture align with divergent regulatory and structural contexts, even being under the same guiding policy framework. This study reveals why some EU Member States achieve durable improvements, others show only temporary breakthroughs, and some experience stagnation or erosion of circularity in their agricultural sectors. Through these contributions, the present study advances the understanding of how EU-level circular economy ambitions are hampered by inherent agricultural realities, and which governance mechanisms are most effective in facilitating transition towards circular economy in the whole EU agriculture.

This paper contributes by constructing a harmonized EU-27 Agricultural Circularity Index (ACI) for 2014–2023 using an expert-weighted TOPSIS framework; linking index dynamics to an indicator-level decomposition that identifies dominant drivers of circularity change; and proposing a rule-based trajectory typology designed as a practical diagnostic tool for policy targeting and monitoring.

To make the analytical focus explicit, the study addresses the following research questions: 1. How do EU Member States differ in agricultural circularity levels from 2014 through 2023?; 2. Which factors predominantly drive these differences in agricultural circularity performance?

1.1. A Brief Overview of Other Factors Determining the Adoption of the Circular Economy Practices in Agriculture

1.1.1. Policy, Legal Frameworks, and Institutional Architecture

The EU is not consistent in reaching its environmental objectives [11]; circular economy is not an exception. Instruments designed for different goals may sometimes conflict [12]. For example, CAP payments historically favoured land-extensive subsidy allocation patterns [13]. The aim was to sustain livestock numbers and extensive feed import models, which in turn, at least partially, come in odds with circularity goals (for example, reducing

feed import dependence, closing nutrient loops). Another drawback of Brussels preferred “one fits all” policies lay in a contextuality of EU Member States’ agricultural sectors. Farm structure (farm size, livestock intensity), natural endowments, and value-chain organization mediate regulatory impacts significantly [14]. It is argued that Northern European countries, whose agriculture can be characterized by intensive livestock sectors and strong local food processing industries (such as the Netherlands, Denmark), do respond differently to nutrient-related regulation compared to Eastern and Southeastern European Union Member States having extensive arable regions [15]. One of the examples of these response heterogeneities was observed in the Netherlands, where very strict regulations on nutrient pollution led to herd reductions and farm consolidation, altering the established market equilibrium. Although this outcome has the potential to facilitate nutrient circularity, due to the economies of scale on remaining farms, it also imposes socio-economic costs, such as reduced employment in agriculture, loss of diversity and diversification in agricultural portfolio, abandonment of traditional farming, etc. [16]. Discretion, which Member States exercise in the implementation of the CAP directives (strategic plans, eco-scheme design, etc.), also contributes to different circular agriculture levels among the EU Member States [17]. Differences arise because some countries prioritize investments in bio-digesters and nutrient recovery [18], while others put emphasis on income support and minimal conditionality [19].

These differences in the implementation of legal frameworks not only make comparison of performance of various EU Member States towards circularity in agriculture even more puzzling, but it is also argued that these parsimonious differences in the implementation of EU regulations transform into substantial variations in levels of adoption of circular practices in EU agriculture. It is also revealed that in the countries where national legislation allocates larger Pillar-2 financial support to infrastructure (processing, manure storage facilities) and training/education, circular practices diffuse more rapidly [20].

Although regulation of the agricultural practices and policy measures aimed at orienting agriculture towards circularity is widely discussed in the literature, its causal influence varies [21]. It is acknowledged that environmental directives, in particular—the EU Nitrates Directive and elements of the Farm-to-Fork agenda—do create compliance pressure that can stimulate manure processing, nutrient recycling, or reduced chemical input use [22]; however, there is evidence that some countries try to at least partially circumvent the most strict adoption of the EU regulation towards circularity in agriculture with the aim of favouring various influential stakeholders groups [23–25], preserving employment in rural regions [26], or of simple populist grounds [27]. Some national EU Member States’ caps on nitrogen and phosphorus application compel farms to seek export or valorization routes for manure to avoid penalties or other financial disincentives [28]. However, regulatory pressure alone does not guarantee the adoption of circularity-oriented farming processes in agriculture: the effectiveness of the legal measures highly depends on enforcement intensity, clarity of implementation rules, and the availability of compliance pathways, which are not always implemented thoroughly [29].

It is considered that institutional factors are among the most important determinants of the evolution of circular practices in agriculture, serving as some form of adoption multipliers, as in the agricultural contexts, the institutional factors favour the development of circular agriculture; thus, its levels are incomparably higher [30]. Advisory services, demonstration farms, and technical support [31–33] are among the most frequently mentioned institutional factors increasing the implementation and, most importantly, the entrenchment of circular practices in farmers’ everyday routines [34]. In the contexts where advisory capacity is weak or dispersed across administrative layers, farmers incur high information search and compliance transaction costs [35], which significantly dampen their willingness

to adopt circular practices. The simplification of certification systems for circularity labelling in agriculture also proved to be important [36]. It is shown that certification systems and product standards, especially those for recovered nutrients, are argued to be essential for legal clarity and downstream market confidence [37], as in rural environments where this compliance framework is absent, farmers' scepticism persists despite obviously proven environmental benefits [38].

The main legal documents, which are designed to facilitate the circular economy practices in agriculture, namely circular material use rate (CMUR), treated-waste capacity ratios, and nutrient-balance metrics, are criticized as they signal policy prioritization over economic reality in some lagging rural regions in the EU periphery [39,40]. It is fair to note that these indicators are more of a monitoring function or targeting tools, as even high values of these indicators do not automatically transmit incentives to farms, if not supported by financial support or are not backed by mature market rules [41]. In summary, it can be stated that regulatory frameworks have an enabling potential, but the true-life adoption outcomes depend on downstream operationalization.

1.1.2. Other Perspectives on the Hindrances and Facilitators of the Adoption of the Circular Practices in Agriculture

The remaining literature review on adopting circular agriculture practices can be divided into several mutually interconnected theoretical streams. One of the most significant theoretical bodies in this area revolves around the economic determinants of the circularity practices in agriculture. High financial constraints act as a barrier in such sectors as anaerobic digestion, manure separation, and nutrient-recovery technologies [42,43]. It is shown that even when circular economy practices promise net economic benefits for the long term, farmers are discouraged from these investments due to uncertainty and liquidity constraints, which leads to a preference for low investment measures such as improved manure application or on-farm composting instead of engaging in systemic transformation of agricultural activities [44]. It is also noticed that economies of scale are very evident in the adoption of circular economy practices in agriculture [45]. Bigger agricultural entities have higher innovation absorption capacity, easier access to finance and technologies required for transformation of their operations on a circularity basis [46], while the smaller, especially part-time farming, which relies on traditions and already established operational patterns, struggle in their transition to the higher levels of circularity [47]. The time horizon also matters. It is proven that if the circular economy adoption economic gains (reduced input costs, efficiency gains) are instant, farmers' willingness to engage in CE practices increases, while if the financial benefits are long term, or even worse, not very certain, farmers' willingness to adopt circularity practices drops sharply [34]. Some studies [48–50] propose the introduction of more sophisticated risk-sharing mechanisms (insurance products, cooperative agreements) as a way to overcome this hindrance towards a wider adoption of circular practices in agriculture. Another economy-related issue impeding the development of the circularity practices in agriculture is market immaturity [51]. This is especially true in the developing world [52]. If bio-based fertilizers or recycled agricultural products are not on demand in the market (which is typically true in the developing world, where cost effectiveness is key and consumers are not willing to pay price premium for ecology-oriented products, which are typically more expensive compared to intensive agriculture harvests), investment risks into machinery required for circularity in agriculture increase substantially [53]. Thus, the adoption of circularity practices is highest where circular economy output markets are stabilized through procurement rules or advanced contract-based vendor practices (e.g., biomethane purchase agreements). While some studies argue for additional subsidies or financial incentives (such as capital grants, guaranteed energy tariffs, and low-interest loans) to foster the adoption of circular prac-

tices in agriculture [54–56], it should be noted that they also contribute to ever-increasing divergence and polarization in agriculture [57]. Multiple distributional assessments reveal that poorly targeted subsidies disproportionately benefit larger, well-capitalized farms, reinforcing structural inequality [42].

Social perspective is also important in analyzing the progress towards circularity in agriculture. Perceived compatibility with existing routines and social legitimacy are mentioned as socio-cultural hindrances for any changes towards different agricultural practices, including ones aimed at greater circularity [58]. In this sense, practices perceived as low-risk, familiar, or values-aligned, i.e., composting to enhance soil health, allow achieving faster innovation (including those related to circular practices) diffusion than disruptive innovations [59]. Cultural attachment to traditional waste disposal (which, due to prevailing false beliefs, is considered environmentally friendly) locks farmers into existing input regimes, which creates behavioural patterns resistant to policy pressure [60]. It is noticed that some positive examples from local community champions can be much more successful in changing these norms compared to any new regulatory regimes [59]. There are also reports revealing gender aspects in the adoption of the circular economy in agriculture [61]. It is shown that women farmers encounter greater procedural and capital access barriers compared to men-led agricultural entities [62,63].

The third theoretical stream investigates the role of technological factors in the development of the circular economy in agriculture. It is noted that much nutrient-recovery machinery was designed keeping in mind large-scale liquid manure operations [64]. On the one hand, this economy-of-scale approach can be praised for its cost effectiveness, making circular economy more competitive and requiring less financial support; on the other hand, it leaves small-scale or mixed-type farmers with very few options available if they are interested in the circular economy practices. This not only leads to persistent adoption gaps between different types of farms [58] but also adds bias to the cross-country comparisons. As some EU Member States are characterized by very large average agricultural holdings (i.e., Czechia), they inherently stand in a better position towards the adoption of circularity practices compared with those EU Member States whose agriculture is dominated by small farms (i.e., Poland) [65]. Infrastructure also determines accessibility to technology. Regional hubs created for composting or digestate processing reduce the need for decentralized investment, increasing participation in them by smaller farms [66]. So, for more remote farms without logistics support (transport vehicles, application services), aggregation costs often outweigh environmental benefits. This becomes even less attractive keeping in mind the carbon footprint generated by transportation activities [67]. Lifecycle evidence increasingly shows strong environmental performance of recycled fertilizers and biogas systems [68], but evidence does not automatically translate into trust and wider adoption of circularity practices. Scepticism persists where technologies cause operational disruptions or where relative performance stability cannot be guaranteed [69].

1.1.3. Selection of Indicators for Measuring the Circularity in Agriculture

While approaches to measure circular economy practices in agriculture started relatively recently—about a decade ago [70]—quite a wide range of indicators for measuring circular practices in agriculture were proposed [71]. Even so, this set of indicators can be arranged according to the measuring object. A significant portion of agricultural circularity indicators focuses on the amounts of manure produced by respective analyzed agricultural entities, as it is considered that manure processing is one of the main issues in achieving circularity in agriculture [72]. This is followed by the amount of treated waste generated during farming operations [73–75], as the circular economy aims to achieve numbers close to zero of untreated waste [76]. The share of organic farming in the whole agricultural

production is the indicator, describing which part of any agricultural system can already be considered environmentally friendly and does not require any substantial efforts in achieving any circularity goals [77]. It is even assumed that organic agriculture is among the main facilitators or proxies towards the development of fully circular agriculture [78]. This is because certification, as an organic element, requires following a management regime towards the use of pesticides, promoting crop rotation, on-farm composting of bio-waste, etc. Gross nutrient balance, an indicator regularly employed as one of the measurement tools of the circularity in agriculture [79–81], is often used in creating various indices or other more sophisticated composite indicators to compare different agricultural systems in their progress in achieving circularity [79]. Another frequently used measure—circular material use rate—is already a composite indicator measuring how much of national material demand is met from secondary (recycled/recovered) inputs and is considered a very universal tool for assessing the state of circularity in agriculture [82,83]. Agricultural overintensification is a major concern in various parts of the world [84]. It requires not only high amounts of pesticides or other chemical fertilizers, but sophisticated irrigation systems are also being used to extract the highest possible harvests [85]. These practices contradict the circularity notion and are considered among the main barriers to achieving circular economy in agriculture [58].

2. Materials and Methods

This section describes the methodological procedure used to calculate the Agricultural Circularity Index (ACI) for the 2014–2023 period. It presents the data preparation steps, the list of indicators, the expert-based determination of weights, the application sequence of TOPSIS, and the treatment of missing data. The set of indicators selected from the scientific literature review was combined into a single ACI using TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution). The ACI was calculated for each Member State separately and for the EU-27 aggregate. TOPSIS was chosen because it allows direct aggregation of heterogeneous indicators (both benefit-type and cost-type), incorporation of expert-assigned weights, and an explicit assessment of each observation's proximity to the ideal solution and distance from the anti-ideal solution. The result is a univocal closeness coefficient on the interval [0, 1], convenient for annual time series and cross-country comparisons. In the final stage weights were fixed according to expert judgement. TOPSIS is also appropriate because it does not require strict parametric assumptions and preserves transparent decomposition—it is possible to identify directly which indicators and which years drove index changes. The choice is supported by the classical TOPSIS description [86] and subsequent methodological reviews showing widespread application of TOPSIS to environmental and agricultural indicator aggregation [87,88], which validates its methodological suitability for constructing this type of index.

TOPSIS method was also chosen, as the main principle of this method is that, of all comparative objects, the best one has the smallest distance from the best variants and the largest distance from the worst variants. TOPSIS normalizes the values of the indicators using the distance between the two values, i.e., vector data normalization [86]:

$$\tilde{r}_{ij} = \frac{r_{ij}}{\sqrt{\sum_{j=1}^n r_{ij}^2}} (i = 1, \dots, m; j = 1, \dots, n), \quad (1)$$

$\tilde{r}_{ij}$ is the normalized value by the TOPSIS method of the j alternative of the i indicator. In our case, the values of i vary from 1 to 6 and $j = n \times k$ alternatives, where n varies from 1 to 28, i.e., indicators for EU-27 countries and common EU in year k that varies from 2014 to 2023 (numerally from 1 to 10); thus, j acquires values from 1 to 280 (28×10).

After normalization of the values, the best solution (variant) V^* , i.e., the maximum value of each maximizing indicator (multiplied by the respective weights ω_i) and the minimum value of the minimizing indicator, was selected. The best variant V^* is calculated according to the formulas [86]:

$$V^* = \{V_1^*, V_2^*, \dots, V_m^*\} = \{(\max_j \omega_i \tilde{r}_{ij} / i \in I_1), (\min_j \omega_i \tilde{r}_{ij} / i \in I_2)\}. \quad (2)$$

The worst-case solution (variant) V^- is calculated according to the formulas [86]:

$$V^- = \{V_1^-, V_2^-, \dots, V_m^-\} = \{(\min_j \omega_i \tilde{r}_{ij} / i \in I_1), (\omega_i \tilde{r}_{ij} / i \in I_2)\}. \quad (3)$$

I_1 is the set of indices of maximizing indicators, I_2 is the set of indices of minimizing indicators, ω_i is the weight of the i indicator.

Then, the total distance D_j^* to the best solutions (variants) V^* and the distance D_j^- to the worst solutions V^- for each of the compared variants (i.e., the values of the indicators for all EU-27 countries and common EU-27 in 2014–2024) were calculated according to the formulas [86]:

$$D_j^* = \sqrt{\sum_{i=1}^m (\omega_i \tilde{r}_{ij} - V_i^*)^2}; D_j^- = \sqrt{\sum_{i=1}^m (\omega_i \tilde{r}_{ij} - V_i^-)^2}. \quad (4)$$

The main criterion C_j^* of the TOPSIS method for each sustainability dimension is calculated according to the formula [86]:

$$C_j^* = \frac{D_j^-}{D_j^* + D_j^-} (j = 1, \dots, n), (0 \leq C_j^* \leq 1). \quad (5)$$

Importantly, ACI is a comparative (sample-based) proximity-to-ideal measure within the observed EU country-year profiles, rather than an absolute score against a fixed external target.

The calculated TOPSIS values range from 0 to 1, i.e., the higher value of ACI reflects a greater overall similarity of the observed indicator profile to the ideal (best-practice) circularity scenario and a larger distance from the anti-ideal (worst-practice) scenario, meaning stronger performance across the component indicators (higher CMUR, larger organic UAA share, lower N per ha and LU per ha after cost-direction reversal, and greater treated-capacity and higher low-input share), given the expert-assigned weights.

The indicator set (Table 1) was adjusted to ensure data consistency, international comparability, and full statistical coverage for the 2014–2023 period. Some primary indicators (for example, gross nutrient balance (GNB) or direct manure mass) showed incomplete data availability, heterogeneous reporting practices, or insufficient coverage in Eurostat series, so we replaced them with more reliable, empirically available proxies (nitrogen per UAA as a proxy for GNB; land use density as a proxy for direct manure mass) or with reconstructed series (Treated_capacity and UAA_share_low_input). These replacements preserve long-term trends and cross-country contrasts while reducing method-driven noise, thereby ensuring the ACI calculation rests on fuller, reproducible Eurostat time series. The applied changes maintain the core informational content (monotonicity and inter country/year differences) required for robust aggregation and interpretation. It is noted that even these new indicators are also covered in the literature and are thus validated and suitable for research. Nitrogen use is suggested by Doyeni et al. [89], land use density by Matysik-Pejas et al. [41], treated waste capacity [90], and share of agricultural land of low input by Selvan et al. [77].

Table 1. Indicators used for the ACI, their units, Eurostat codes, and direction.

NR.	Primary Replaced	Indicator Name	Unit	Implemented Calculation (What Was Performed) and Data Sources	Direction
1	-	Circular material use rate (CMUR)	%	CMUR (direct export from cei_srm030), Eurostat	Benefit
2	-	Area under organic farming (organic UAA)	%	$\text{Organic_area_ha}/\text{UAA_ha} \times 100$ (sdg_02_40/AUCT_EAA), Eurostat	Benefit
3	Gross Nutrient Balance (GNB) $\rightarrow$ N/UAA (proxy)	Consumption of inorganic fertilizers per UAA (N/UAA)	kg N/ha	$\text{Total_N_fertilizer_kg}/\text{UAA_ha}$ (aei_fm_usefert/AUCT_EAA), Eurostat	Cost
4	Direct manure mass $\rightarrow$ LU_density (proxy)	Livestock density (LU/ha)	LU/ha	LU_density (tai09/apro_mt_livestock), Eurostat; missing years linearly interpolated	Cost
5	Original treatment indicator $\rightarrow$ revised inverted capacity ratio (no major mineral)	Treated waste (excl. major mineral) to the generated in agriculture, forestry, and fishing (treated capacity)	%	$\min(100, (\text{Total_treated_waste_all_sectors_excl_major_mineral}/\text{Total_generated_waste_in_Agriculture_Forestry_Fisheries}) \times 100)$, (EWC-STAT), Eurostat	Benefit
6	Share of irrigated UAA $\rightarrow$ UAA_share_low_input	UAA share managed by low-input farms (UAA_share_low_input)—extrapolated to 2022–2023 (low input)	% UAA	Observed 2014–2021 exported; 2022–2023 = country-level OLS projection on 2014–2021 (aei_ps_inp), Eurostat	Benefit

To assess whether selected proxy indicators preserve the core informational content of the original variables, we performed a correlation check using overlapping country–year observations. The proxy for gross nutrient balance, i.e., consumption of inorganic fertilizers per hectare of utilized agricultural area (N/UAA), is strongly and statistically significantly correlated with the original gross nutrient balance indicator (Pearson $r = 0.65$; EU Member States; annual data). This indicates that N/UAA captures the dominant cross-country and temporal variation in nutrient pressure relevant for circularity assessment, while providing superior data completeness and consistency for 2014–2023. Hence, using N/UAA as a proxy supports robust ACI aggregation at the EU-27 level without distorting long-term trend interpretation.

To validate the proxy for direct manure mass and the spatial concentration of organic residues, livestock density (LU/ha) was compared with Eurostat data on total livestock units associated with manure storage and application. Although absolute manure mass is available only for selected benchmark years, cross-sectional comparison shows that countries with high total livestock units (e.g., the Netherlands, Belgium, Denmark, Germany, and France) also exhibit high livestock density per hectare. This supports LU/ha as an effective proxy for spatial manure pressure, highlighting where valorisation infrastructure and nutrient-recovery solutions are most needed. Given data constraints, the proxy pri-

oritizes spatial comparability over temporal precision, which is appropriate for EU-wide circularity assessment.

CMUR is widely used as a system-level proxy for material recirculation in circular-economy monitoring [82,91]. Organic_UAA is used as a proxy for low-external-input production and certified agro-ecological management practices [20]. N_per_ha reflects nutrient pressure and dependency on external fertilizer inputs, commonly treated as a core constraint to circular nutrient management [80,92]. LU_per_ha captures livestock-driven spatial concentration of manure and organic residues and is routinely linked to nutrient-surplus risks [28,72]. Treated_capacity represents formal processing capacity for biowaste/organic residues and is discussed as a necessary but not sufficient condition for circular flow realization [93,94]. UAA_share_low_input reflects the diffusion of less input-intensive practices and is frequently emphasized as a transition pathway where market and advisory systems support adoption [20,95].

Missing observations were handled conservatively to preserve cross-country comparability. For LU_density, isolated missing years were linearly interpolated; for UAA_share_low_input, the most recent years were projected using a simple trend extrapolation consistent with the approach described in Table 1 notes. EU-27 aggregates were taken directly from Eurostat where available; where only country series were available, EU-27 values were constructed as consistent aggregates (e.g., ratios computed from EU totals for numerator and denominator) to avoid distortions from simple averaging.

Cost-type indicators (N_per_ha and LU_per_ha) were designated as “cost” because larger values indicate an undesirable effect on circularity as follows: higher mineral fertilizer use (kg N/ha) signals greater reliance on external inputs and higher risk of nitrogen losses, while higher livestock density (LU/ha) indicates more concentrated manure production and greater logistical and processing challenges. Therefore, prior to normalization, these series were directionally inverted so that higher transformed values correspond to a more favourable effect and are compatible with benefit-type indicators.

Brief notes on imputations: missing years for the LU_density indicator (tai09/apro_mt_livestock) were filled by linear interpolation; UAA_share_low_input was extrapolated for 2022–2023 using an OLS forecast based on 2014–2021 data. All imputed or extrapolated estimates did not change the interpretation of long-term trends.

Differential weights were applied to all indicators—the weight allocation reflects both the methodological contribution of each indicator to the circularity concept (for example, a larger systemic effect attributed to CMUR) and the consolidated priorities of the expert panel. Weights were therefore set on the basis of seven expert judgments with reproducible documentation of each expert’s input; this approach preserves proportional influence across indicators while providing a clear argumentative justification for each weight. A seven-expert panel is considered sufficient for these priority settings because consensus-based practices commonly use smaller, thematically selected expert panels (typically 5–15 experts), which secure deep subject matter expertise without undue administrative burden.

Weights for the six indicators were elicited from a purposive panel of seven domain experts to reflect relative contributions of each indicator to agricultural circularity. The panel size balanced domain coverage and practicability as follows: seven experts provided diverse disciplinary perspectives while keeping the elicitation manageable and auditable. Experts were purposively selected against explicit criteria to ensure direct relevance to agricultural circularity: all seven have at least five years of practical or research experience specifically on circular economy applications in agriculture (e.g., circular nutrient management, organic farming, manure logistics, agricultural waste treatment, low input farming practices, or agri-data analysis), hold a minimum of a Master’s degree (PhD or

equivalent professional seniority preferred), demonstrate a substantive contribution to the field (peer-reviewed publication or major applied project), have experience working with official time series (e.g., Eurostat), and can provide auditable, written justifications for their weight allocations; therefore, the resulting seven-expert panel combines thematic depth, data familiarity, and documented rationale for the elicited weights.

Each expert allocated 100 points across the six indicators; the column means of these allocations form the final weight vector applied in the TOPSIS aggregation. The expert score matrix is presented below (Table 2), as well as the derived column sums and means (final weights), and a concise explanation of the numerical procedures used to convert scores to ranks and to compute Kendall's W and its statistical significance.

Table 2. Expert score matrix (E1–E7, points; each row sums to 100).

Expert	CMUR	Organic UAA	N_per_ha	LU_per_ha	Treated_Capacity	Low_Input_Share	Row Sum
E1	35	10	25	15	5	10	100
E2	30	15	20	10	21	4	100
E3	25	15	25	15	5	15	100
E4	35	5	20	20	10	10	100
E5	20	25	20	15	10	10	100
E6	25	15	20	15	10	15	100
E7	26	20	24	15	9	6	100
Column sum	196	105	154	105	70	70	700
Mean (weight)	0.280	0.150	0.220	0.150	0.100	0.100	1.000

Each expert's point allocation expresses ordinal and cardinal judgments about indicator importance. We converted the elicited scores into the final weight vector by taking the arithmetic mean of each indicator's column (column sum divided by number of experts) and dividing by 100 to produce a normalized weight between 0 and 1. This deterministic averaging preserves the relative emphasis each expert placed on indicators while producing a single, reproducible weight set for TOPSIS as follows: CMUR 0.28; Organic UAA 0.15; N_per_ha 0.22; LU_per_ha 0.15; Treated_capacity 0.10; Low_input_share 0.10.

Different calculations of panel agreement—converting each expert's point allocations to ranks (with average ranks for ties), computing Kendall's W with and without the standard tie correction and confirming significance via the chi square approximation—all return consistent evidence of substantial concordance ($W \approx 0.64$, $\chi^2 \approx 22.4$, $p < 0.001$). These concordant results, despite minor methodological variations, show that the elicited weight vector is robust to reasonable procedural choices and therefore appropriate for use in the TOPSIS-based ACI aggregation. Consequently, the consolidated weights can be confidently applied to evaluate agricultural circularity changes across EU Member States over 2014–2023.

Trajectory Typology (Rule-Based Classification)

Member States were grouped into four trajectory types using three quantitative criteria as follows: (i) baseline ACI level, (ii) average annual ACI change over 2014–2023, and (iii) indicator-level decomposition identifying which ACI components predominantly drive the observed trajectory. The typology is therefore analytical and rule-based; country narra-

tives are used only to contextualize the quantitatively derived patterns, not to determine group membership.

3. Results and Discussion

Before turning to individual country trajectories, three overarching empirical patterns emerge from the ACI results. First, aggregate EU-27 circularity improved only marginally over the analyzed period, masking substantial divergence among Member States. Second, countries with initially high circularity levels did not necessarily sustain progress over time, while several lower-baseline systems achieved short-term improvements. Third, structural characteristics—notably live-stock intensity, nutrient pressure, and treatment capacity—systematically shape observed circularity paths, justifying the use of a trajectory-based typology.

After applying TOPSIS transformations and expert-determined weights, the Agricultural Circularity Index (ACI) values for all EU Member States in 2014 and 2023 provided the empirical baseline for assessment. The EU-average ACI increased from 0.3738 to 0.3963 over the period, corresponding to an average change of about 0.0025 ACI points per year, but this aggregated growth conceals substantial cross-country heterogeneity. At the country level, ACI values ranged between 0.2293 and 0.5462 during the study period. The lowest ACI, 0.2293, was recorded in Ireland in 2021, and the highest, 0.5462, in Estonia in 2022. Individual ACI values alone do not constitute causal evidence; they must be interpreted alongside a quantitative decomposition by the constituent ACI indicators and with the timing of relevant policy and project events, in order to distinguish structural changes from episodic impulses (Figure 1).

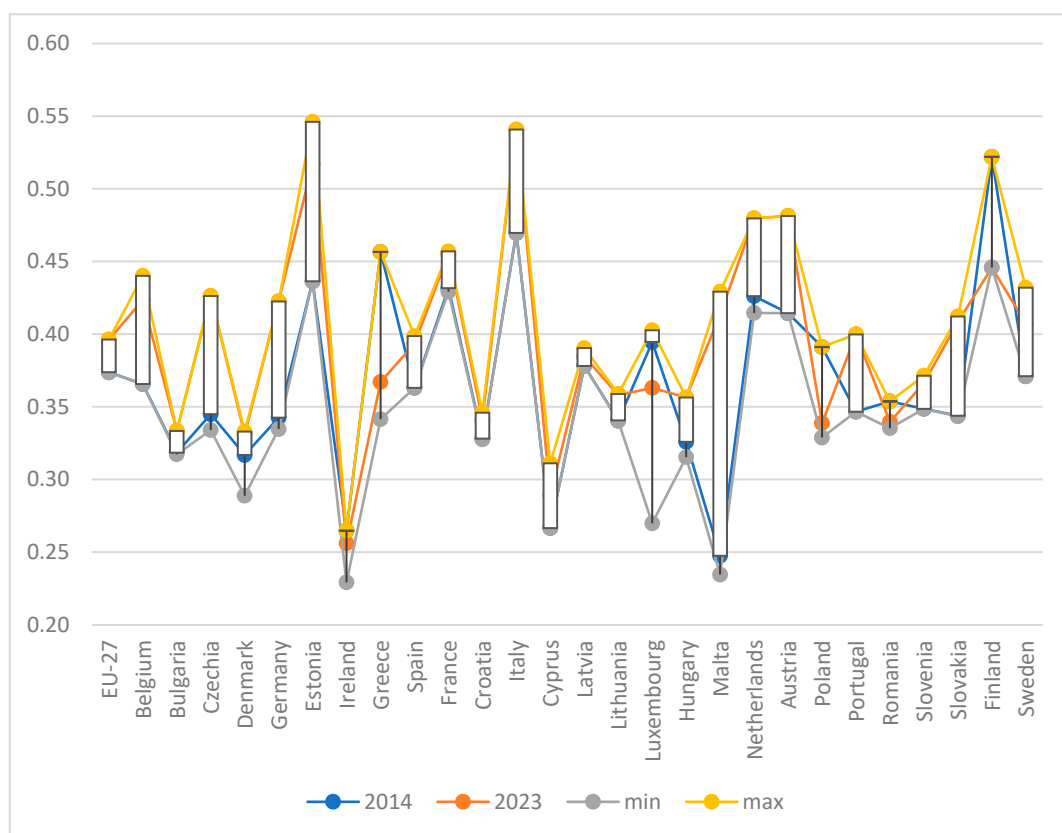


Figure 1. ACI values for 2014 and 2023, with country level, EU-27 minimum and maximum.

3.1. Trajectory Types: Cross-Country Synthesis

Based on the joint evidence from baseline ACI level, average annual change (2014–2023), and indicator-level decomposition, four recurrent trajectory patterns emerge.

Durable promoters are characterized by sustained ACI growth driven by synchronized improvements in circularity-favouring components (typically CMUR and/or Organic_UAA increasing alongside realized gains from treated_capacity, with nutrient pressure not intensifying after cost-direction reversal).

Short-term breakthroughs display sharp ACI increases that are not fully consolidated over time, most often reflecting faster improvements in treated_capacity than in CMUR/Organic_UAA uptake, consistent with a commissioning–utilization gap.

High baseline, eroding systems start from relatively high ACI values but stagnate or decline as intensification pressures (rising N_per_ha and/or LU_per_ha) offset improvements in other components.

Finally, mixed/stagnating trajectories show weak net change and mixed decomposition signals, indicating that changes in capacity and practice diffusion do not translate into durable circular flows. The country cases below are therefore presented as illustrations of these type-level patterns and their policy context, rather than as the basis for classification.

The interpretation of ACI trajectories rests on the weighted interaction of the following six interdependent indicators: material recirculation rate (CMUR), share of organic land (Organic_UAA), fertilizer intensity (N_per_ha), livestock density (LU_per_ha), treated capacity, and the share of low-input plots. Each Member State's trajectory is therefore read as a configuration of these components: in practice, a durable increase in ACI typically requires at least two synchronized favourable shifts (for example, the operational uptake of new treated_capacity combined with an expansion of Organic_UAA and/or rising CMUR). The country illustrations that follow describe how these indicator configurations manifest over time and how they relate to relevant policy context.

I. Durable promoters (structural, cumulative growth)—Estonia, Latvia, and Poland (in selected aspects)

Estonia remains the paradigmatic durable promoter: ACI rose from 0.4363 in 2014 (Figure 2) to 0.5172 in 2023 (mean annual 0.009), organic share increased from 15.96% UAA (2014) to 22.80% (2023), CMUR rose from 11.3 (2014) to 18.1 (2023), and the treated capacity index accelerated after 2019 (from 8.32% in 2014 to 36.29% in 2023); these statistical changes cluster around a clear two-stage sequence: contraction of conversion activity in 2016–2018 followed by concentrated commissioning and throughput growth in 2019–2021. These observed gains are explained both by time-aligned technical sequencing between conversion, commissioning, and throughput, and by concrete institutional conditions: Estonia's national RDP implementation practices and guidance that aligned conversion incentives with coordinated commissioning windows, together with stronger application of ex post throughput checks and more active producer-organization support, helped ensure that installed capacity found real offtake and supported sustained farm-level transitions [96].

Latvia displays a regionally concentrated durable-promoter dynamic: ACI was broadly stable to slightly positive (from 0.3781 to 0.3846). Organic share rose from 10.86% in 2014 to 15.08% UAA in 2023, while treated capacity and CMUR showed episodic subnational upticks (treated_capacity with marked year-to-year spikes in 2017–2022), producing durable effects only where land use change and capacity deployment coincided. This pattern is associated with localized administrative practices, cluster-level coordination-led aggregation that allowed subnational monitoring, rapid technical assistance, and temporary resource concentration to turn episodic capacity spikes into functioning durable pockets [96].

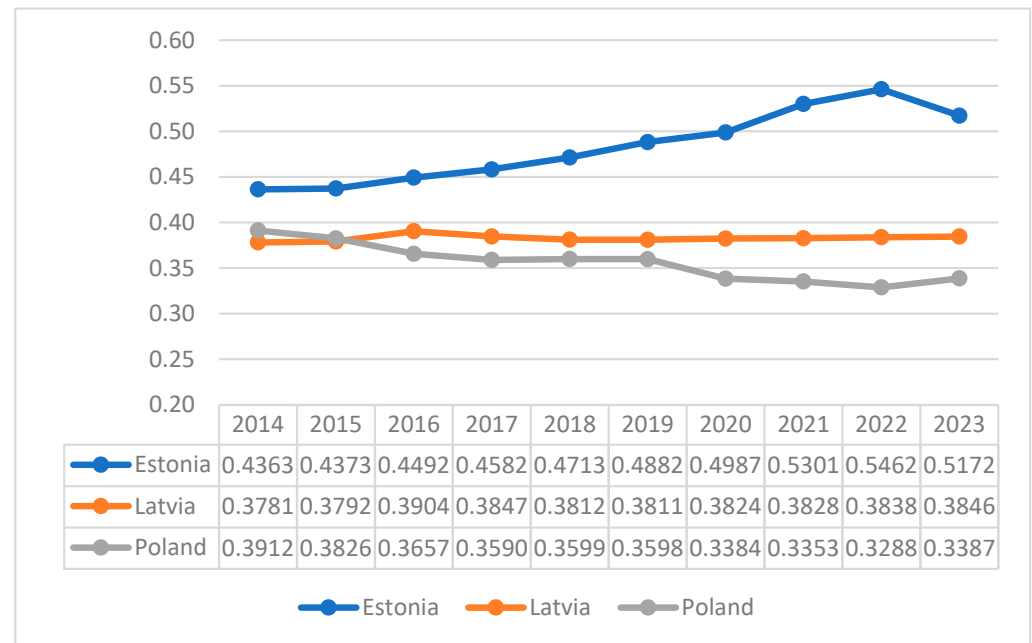


Figure 2. ACI values for 2014–2023 in Estonia, Latvia, and Poland.

By contrast, Poland is a spatially heterogeneous, conditional promoter, and recorded a national ACI decline from 0.3912 (2014) to 0.3387 (2023) despite treated capacity growth (from 15.556% to 17.240%) and an expansion of low-input share (from 32.3% to 39.7% UAA), because CMUR fell (from 13.0 to 7.5) and organic area remained essentially flat (from 4.56% to 4.35% UAA); the critical empirical insight for Poland is the 2016–2021 timing mismatch in which commissioning and registered capacity rose without contemporaneous CMUR increases or sustained national organic area gains, a mechanism institutional reviews link to weak ex post verification, gaps in staged payment or market-integration requirements and implementation delays, so capacity registration expanded administratively without converting into broad supply-chain throughput or mass farm practice change [93].

II. Breakthrough countries (rapid, concentrated gains)—Malta, Cyprus, and Portugal (selected aspects)

Malta sits at the core of this cluster: national ACI rose (Figure 3) from 0.2475 (2014) to 0.4135 (2023) (mean annual +0.0184). The empirical pattern is consistent with a financing plus delivery model in which temporally concentrated public finance and fast commissioning produce rapid national gains; concentrated investment and swift project delivery (project windows 2017–2020 with commissioning concentrated in 2018–2020) accounted for large short-term Δ ACI contributions in the supplied series (treated capacity spikes, CMUR jump, and fertilizer use reductions) [96]; The persistence of such gains, however, depends on verified throughput and subsequent market and farmer uptake: the evaluation literature and EU practice notes document frequent cases where installed capacity did not translate into sustained material flows unless commissioning was followed by measured processing tonnages, functioning aggregation, and stable offtake arrangements [91,97].

The Maltese time series illustrate this profile: the largest decomposed contributions to Δ ACI align with (a) rapid processing infrastructure deployment and commissioning (captured by treated capacity spikes), (b) a marked CMUR increase, and (c) fertilizer use reductions, but these concentrated gains carry a reversal risk where throughput verification and market integration remain incomplete [96].

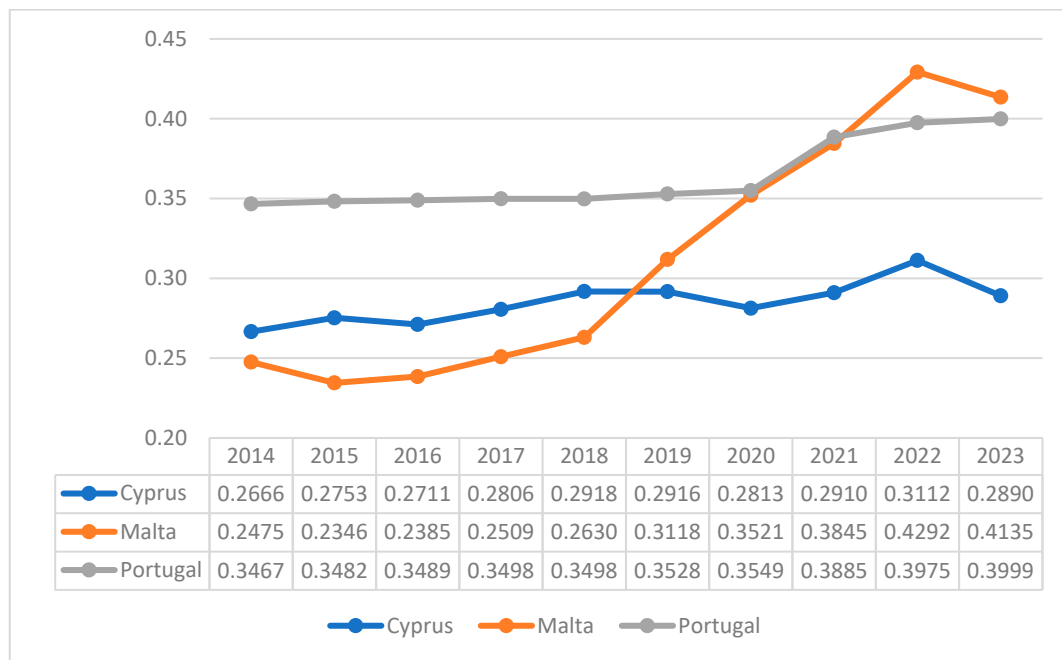


Figure 3. ACI values for 2014–2023 in Cyprus, Malta, and Portugal.

Cyprus displays the same concentrated mechanism at smaller scale: ACI moved from 0.2666 (2014) to 0.2890 (2023), with a notable uptick concentrated in 2021–2022 (0.2813 in 2020 to 0.2910 in 2021 and to 0.3112 in 2022 before 0.2890 in 2023). This ACI trajectory is temporally consistent with the indicator shifts you reported: organic share rose from 3.63% UAA (2014) to 8.61% (2023) and CMUR increased from 2.2 (2014) to 5.4 (2023), while treated capacity figures showed pronounced year-to-year swings consistent with episodic commissioning. The sequence in the series—capacity commissioning spikes followed by short-term CMUR and organic area gains and then partial reversion—matches case study evidence that such signatures typically reflect a small number of high-impact investments rather than broad structural change unless those investments are followed by sustained uptake and integration measures [91].

Portugal's national ACI shows a late period acceleration from 0.3467 (2014) to 0.3999 (2023), with the steepest rise occurring in 2021–2023 (0.3549 in 2020 to 0.3885 in 2021 and to 0.3975 in 2022, followed by 0.3999 in 2023). Over the same interval indicators' value dynamics show organic area expansion (from 5.74% UAA to 22.47% UAA per 2014–2023) and increases in low-input share (from 32.3% to 44.0%), while national CMUR moved only modestly and treated capacity series show strong year-to-year variability. Where the late organic expansion coincided with concentrated commissioning of treated capacity and logistics upgrades the result, as reflected in the ACI time series, was rapid national gains; where commissioning and market/aggregation measures were not synchronous, ACI acceleration was weaker. Cross-country evaluations underline that such single-block financing plus fast delivery often produces transient indicator spikes unless complemented by post-commissioning market measures and verified throughput [96].

III. High baseline but erosion risk cases—Finland, Greece, and Spain

Finland and Greece exhibit a clear erosion trajectory, demonstrating that a high initial ACI does not guarantee stability—Finland's ACI values fell from 0.5220 (2014) to 0.4458 (2023) (avg. annual decrease equal to 0.0085), Greece's from 0.4566 to 0.3671 (avg. annual decrease—0.0099), while Spain maintained a moderate national level but showed indicator dynamics that can increase erosion risk, i.e., shifts in metrics that reduce supply stability

and throughput reliability, amplify seasonal variability, and weaken farm-to-processing synergies (Figure 4).

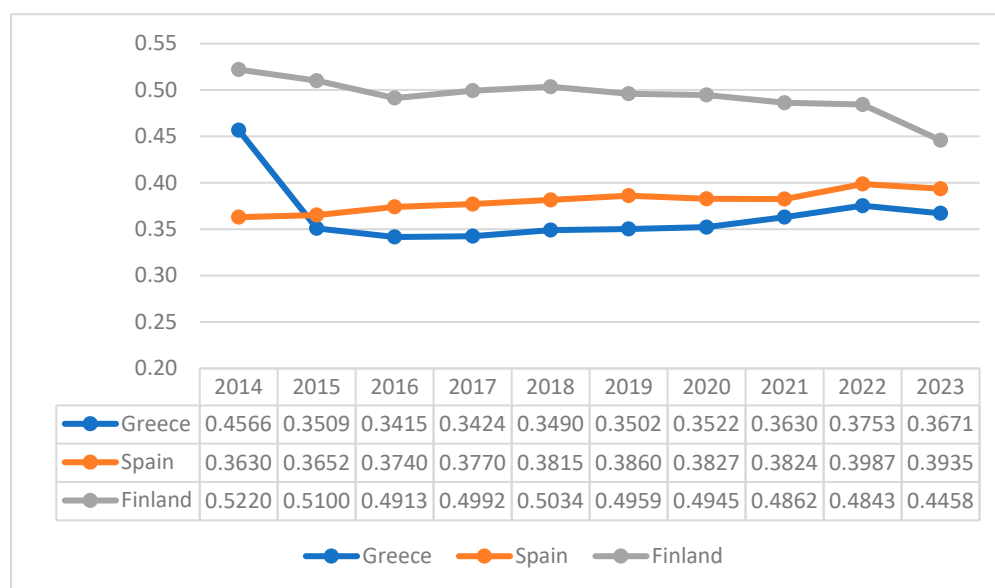


Figure 4. ACI values for 2014–2023 in Greece, Spain, and Finland.

Decomposition assigns the observed declines mainly to three interacting variables. First, there are shifts in field intensity, visible as volatility and net increases in nitrogen application per hectare (for example, Greece from 30.69 to 33.02 kg N/ha over the period), which raise baseline input intensity. Second, there are changes in livestock density that amplify pressure on nutrient cycles (Greece from 0.51 in 2014 to 0.73 in 2023; Spain from 0.63 to 0.74). Third, problems absorbing treated or processed capacity are present: time series for processing capacity show episodic commissioning, but actual throughput frequently fails to match installed capacity (Finland’s processed capacity proxy declined by about 1.65 times; Greece’s fell by more than 147 times). Thus, new infrastructure has not translated into a steady, increased supply to the farm level. Organic area expansion and low-input adoption in these contexts have been either delayed or too limited to offset those negative shifts. Taken together, changes in N/ha, livestock density, and treated capacity/processed throughput explain a large share of the ACI decline (in Greece roughly -0.04 attributable to N/ha and -0.03 to treated capacity for the 2014–2023 period). Institutional evaluations and methodological studies further show that RDP capital interventions often lack robust ex post throughput verification, suffer implementation delays, and depend on weak aggregation and market linkages—conditions that are empirically associated with limited long-term uptake of infrastructure and of the complementary field-level measures needed to secure durable circular outcomes [92–94].

IV. Mixed trajectories—Lithuania, Romania, and Hungary

Lithuania, Romania, and Hungary form a mixed trajectory group. Infrastructure expansion has in some cases not been accompanied by consistent, sustained-on-farm changes during the observation period [93]. In Lithuania (Figure 5) ACI rose from 0.3406 (2014) to 0.3580 (2023) while the processed capacity proxy increased roughly 1.7 times and low input UAA fell from 35.5% to 22.3%, indicating that infrastructure growth produced a short-term ACI impulse (approx. $+0.04$ – 0.06 per 2014–2023 period) but farm-level adaptation and support for low-input practices did not sufficiently follow [94].

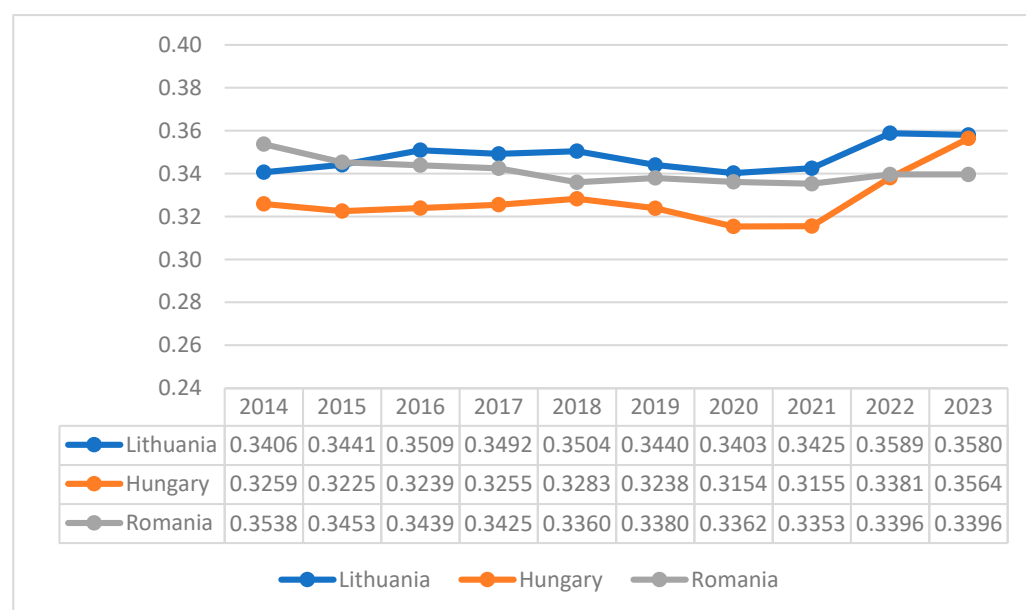


Figure 5. ACI values for 2014–2023 in Lithuania, Hungary, and Romania.

In Romania ACI declined from 0.3538 (2014) to 0.3396 (2023), low-input share fell dramatically (from 29.0% to 5.2%), and the processed capacity proxy decreased by more than 1.3 times, so here intensification and land use loss dominate regardless of regional capacity deployments [94]. In Hungary ACI rose from 0.3259 (2014) to 0.3564 (2023), processed capacity proxy increased substantially about 2.5 times, and low-input share rose overall from 24.1% to 33.3%; however, impacts are heterogeneous—in some areas capacity growth coincides with stronger aggregation and offtake measures (positive throughput), while in others weak market linkages and monitoring leave facilities underfilled (Low-Input Farming and Territories [95]. These patterns support the causal hypothesis that a temporal mismatch in which funding precedes commissioning, followed by delayed throughput, then farm uptake, and ultimately land use change, combined with weak producer aggregation and the absence of throughput-based conditionality or ex post monitoring, weakens investment durability and can produce mixed or degrading ACI outcomes; institutional evaluations and applied studies document these mechanisms and should be cited to substantiate the claim [93–95].

3.2. Complementary Innovation Leaders—ACI Comparison and Interpretation

Several EU Member States, notably the Netherlands, Germany, France, Denmark, and Austria, merit brief mention as circular agriculture innovation leaders, even though they were not separated into our I–IV ACI clusters: the Netherlands ACI moves from 0.4262 to 0.4797 (2014–2023), Germany from 0.3426 to 0.4225 (2014–2023), France from 0.4316 to 0.4552 (2014–2023), Denmark from 0.3169 to 0.3310 (2014–2023), and Austria from 0.4145 to 0.4813 (2014–2023); these time series indicate that these countries (excl. DK) generally lie above the EU mean or show sustained positive ACI trajectories (Figure 6), so they can be flagged as complementary “innovation leaders” without undermining ACI’s validity [98].

ACI is a TOPSIS composite built from six chosen indicators (CMUR, organic area, N/ha, livestock density, processed capacity proxy, and low input UAA); therefore, its construction is particularly sensitive to land use, nutrient intensity, and processing capacity signals. Many strengths of the countries named above—large-scale nutrient recycling installations, biometane/AD deployment, prevalence of long term offtake contracts, strong producer organizations, and rapid R&I diffusion—are captured only partially or indi-

rectly by those six signals, which helps explain why functional leadership in innovation does not always produce a distinct ACI cluster [91]; Institutional and empirical evaluations document the mechanisms behind this explanatory gap: producer organization strength and market aggregation facilitate offtake and value-chain absorption, while stricter ex post conditionality and focused monitoring increase the durability of infrastructure investments—factors that raise systemic circularity even where short-term changes in ACI components are moderate [91]. Applied research and H2020 syntheses further show that farmer adoption of low-input and nutrient-recycling practices depends on bundled support (technical assistance, targeted incentives, and market arrangements), meaning innovation-led system change may progress through governance and market channels that ACI's six indicators only partially reflect [95].

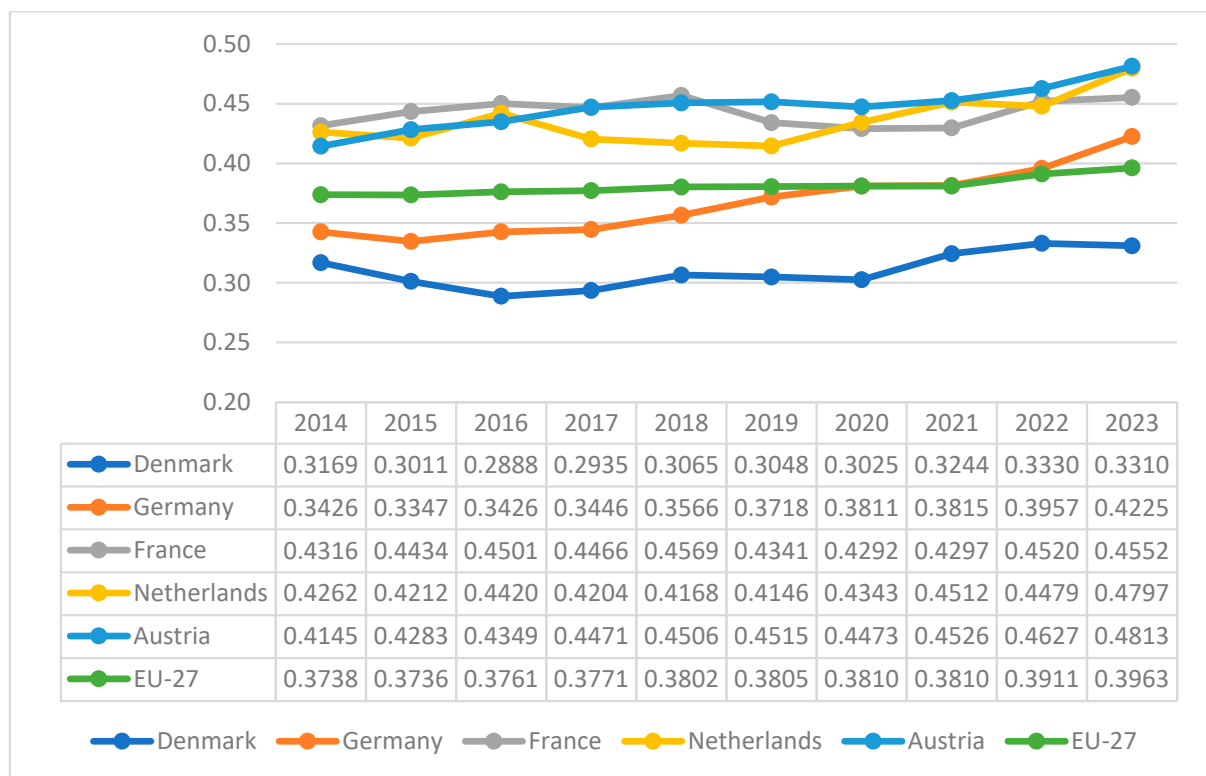


Figure 6. ACI values for 2014–2023 in Denmark, Germany, France, Netherlands, Austria, and EU-27.

4. Interpretation and Policy Conclusions

The Agricultural Circularity Index (ACI), computed with TOPSIS from six indicators (weights: CMUR 0.28; organic area 0.15; N/ha 0.22; LU/ha 0.15; treated_capacity 0.10; low-input share 0.10), shows a modest aggregate improvement in EU circularity between 2014 and 2023 (EU-27 ACI rose from 0.3738 to 0.3963). Member States' trajectories, however, reveal clear and policy-relevant patterns. The analysis indicates that lasting, meaningful ACI gains require at least two synchronized processes: (1) increased material recirculation (higher CMUR or expansion of organic area) and (2) functioning processing throughput (treated_capacity that translates into verified processing tonnes and stable offtake). When these two elements align, ACI rises consistently; where treated_capacity grows in isolation without CMUR or low-input expansion, or where intensity indicators (N/ha, LU/ha) increase, ACI gains are weak or reverse.

4.1. Empirical Typologies and Concise Findings

Durable promoters. Estonia and parts of Latvia show sustained ACI growth where investment packages combined infrastructure rollout, measures that expanded organic area, and actions that strengthened market uptake. Temporal coincidence of commissioning, CMUR increases, and treated_capacity expansion strengthens the causal plausibility that integrated action produced the observed results.

Breakthroughs. Malta, Cyprus, and selected Portuguese cases demonstrate that concentrated funding windows with rapid commissioning can produce pronounced short-term ACI jumps. These breakthroughs are effective in the short run but depend on market integration and verified throughput to persist; if those conditions are absent, gains tend to revert.

Erosion risk. Finland and Greece illustrate that a high starting ACI does not guarantee stability: rises in intensity (N/ha, LU/ha) or installed capacity that is not absorbed by supply chains are associated with ACI decline.

Mixed trajectories. Lithuania, Romania, and Hungary typify mixed outcomes where administratively recorded increases in treated_capacity do not always convert into higher CMUR or low-input uptake. Therefore, national ACI changes remain muted or depend on local market conditions.

The ACI 2014–2023 evidence confirms that strengthening circularity in agriculture is a dynamic, multi-layered process. Long-term ACI improvement depends not on one-off capacity increases but on synchronized investment packages, verified throughput, and active intensity management. Policy instruments that combine conditional payments, packaged investments, and project-level monitoring have the greatest potential to turn ACI growth into genuine, persistent changes in farm practice and material flows rather than into temporary statistical signals.

Building on these trajectory patterns, the policy implications can be derived consistently at the type level by aligning dominant driver combinations with plausible implementation channels.

Policy conclusions can be derived consistently at the trajectory-type level by aligning typical ACI driver combinations with plausible implementation channels, without changing the index-based design of the study. For durable promoters, the empirical pattern (CMUR and/or Organic_UAA rising alongside treated_capacity, with stable or declining N_per_ha and LU_per_ha) is most consistent with policy mixes that convert installed capacity into verified circular flows, i.e., investment support combined with monitoring and throughput verification, offtake/aggregation arrangements, and advisory support that accelerates uptake. In short-term breakthroughs, treated_capacity improves faster than CMUR/Organic_UAA, suggesting a “commissioning gap” where funding and infrastructure roll-out precede real utilization; here, staged payments tied to verified throughput and measures that strengthen demand-side uptake can plausibly stabilize gains. High baseline but eroding systems display intensification pressures (rising N_per_ha and/or LU_per_ha) that offset gains from capacity or organic uptake, indicating that investment measures need to be complemented by nutrient-pressure management, precision/advisory instruments, and tighter ex post checks to prevent rebound effects. Finally, mixed or stagnating trajectories—where capacity signals do not translate into sustained CMUR or low-input diffusion—point to coordination constraints (fragmentation, limited aggregation, and weak offtake logistics), implying that policy effectiveness hinges on linking infrastructure support to market integration and credible monitoring rather than expanding capacity alone.

4.2. Analytical Interpretation, Policy Measures Implied by the ACI Dynamics

Decomposing ACI shows that the principal drivers of national trajectories are CMUR, treated_capacity, and N/ha, and their interactions determine whether infrastructure investment becomes a real increase in material recirculation. Time alignment matters: funding and commissioning windows cause capacity spikes; if these spikes are not accompanied by demand-side measures (aggregation, offtake) before or after commissioning, CMUR does not rise proportionally and the net ACI effect weakens. Rising intensity (higher N/ha or LU/ha) can cancel out infrastructure and organic gains because increased external input dependence reduces the system-level circularity benefit.

Conditioned payments. Capital measures should be linked to commissioning and to verified throughput. Structuring payments as an advance plus a final tranche released only on documented processing tonnage or agreed throughput metrics creates a direct incentive for capacity to be used, not merely registered.

Packaged investments. RDPs and similar instruments should fund infrastructure alongside measures that expand organic area and strengthen offtake and aggregation (producer organizations, market facilitation). CMUR increases only where demand channels exist; infrastructure alone is insufficient.

Intensity management. Regions or sectors with rising N/ha or LU/ha require targeted measures (precision agriculture support, advisory services, and adapted subsidy design) to reduce fertilizer use and manage livestock density, thereby protecting ACI gains from erosion.

Monitoring and triangulation. Treated_capacity figures must be triangulated with throughput data, existence of offtake arrangements, and project reports. ACI interpretation should integrate these project-level verification layers to distinguish structural change from administrative capacity registration.

4.3. Limitations and Guidance for Interpretation

Facilitators: verified throughput and offtake arrangements that convert installed capacity into real circular flows; bundled investment packages combining infrastructure with advisory and market integration; and stable monitoring systems that reduce implementation gaps.

Constraints: intensification pressures (rising N_per_ha and/or LU_per_ha) that offset gains from capacity or organic uptake; fragmented farm structures and limited aggregation that weaken offtake and logistics; and non-harmonized reporting of key market/throughput variables.

Technological adaptability and farm structure matter for interpretation: the same policy instrument can yield different ACI responses depending on whether farms have access to advisory services, financing, machinery, and stable offtake channels. In systems dominated by smaller farms, adoption may be constrained by transaction costs and limited investment capacity, while larger and more specialized systems may face stronger rebound risks through intensification. Because harmonized EU-wide annual series disaggregated by farm size are not consistently available, this study treats these channels as contextual mechanisms rather than quantified drivers; we flag farm-scale integration as a priority for future work.

ACI is sensitive to weight choices and to specific proxy or imputation decisions (N/ha used as a GNB proxy; LU_density interpolations; and extrapolated low-input shares for 2022–2023). Expert weight consistency (Kendall's $W \approx 0.64$) and sensitivity checks indicate that core typologies are robust under realistic alternative assumptions, but results must be read with caution where treated_capacity reflects registered capacity rather than documented throughput. Hence, ACI trends are most credible when assessed alongside

project-level throughput records and RDP timelines to distinguish durable effects from transitory, administratively driven signals.

4.4. Recommendations for Further Research

Integrate throughput-based data: build national datasets linking registered capacity to yearly processing tonnes and offtake contracts to better capture whether treated_capacity translates into real CMUR increases and durable circular flows.

Expand sensitivity testing: run systematic weight-scenario analyses and compare alternative normalisations (for example z-scores) to quantify index robustness across plausible methodological choices.

Undertake subnational analysis: NUTS2-/NUTS3-level trajectories can identify where local policy packages create concentrated durable-promoter effects or mitigate reversal risk.

Conduct counterfactual modelling: simulate ACI trajectories holding treated_capacity or low-input shares constant to quantify the marginal contributions of infrastructure and land use change.

Future research could extend the ACI framework by integrating more detailed market-level indicators and farm-scale data where harmonized EU-wide series become available, allowing deeper analysis of causal mechanisms behind observed circularity trajectories.

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