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Article

Functional Fragmentation as a Structural Determinant of Agricultural Competitiveness: Evidence from the European Union

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Abstract

Agriculture in the European Union operates within a complex environment shaped by biological constraints, technological change, institutional frameworks and increasing climate variability. While existing research has largely explained agricultural competitiveness through productivity, technological adoption or policy incentives, less attention has been given to how the internal organisation of production-related functions constrains performance. This study addresses that gap by empirically examining the role of agricultural functional fragmentation and structural incompatibility in shaping agricultural competitiveness across EU Member States over the period 2004–2023. Unlike related concepts such as structural complexity, diversification or farm management complexity, which describe the variety of activities within agricultural systems, this framework focuses on the simultaneity and biological rigidity of core functions that must be coordinated in parallel, generating cumulative coordination burdens. Using harmonised data from FAOSTAT, FADN, WDI, WGI and WMO, the analysis constructs a multidimensional competitiveness index and a system-level measure of functional fragmentation. The empirical strategy combines descriptive analysis with fixed-effects panel regressions, interaction models, instrumental-variable estimations and extensive robustness checks. The results show that higher functional fragmentation is consistently associated with lower agricultural competitiveness, while technological intensity exerts a stable positive effect. Climate anomalies over the observed period are linked to modest average performance gains rather than losses, and institutional quality alone does not offset structural constraints. Overall, the findings highlight functional fragmentation as a persistent structural determinant of agricultural competitiveness and underscore the importance of system-level coordination alongside technological progress.

Keywords: functional fragmentation; agricultural competitiveness; structural constraints; technological intensity; institutional quality; European Union agriculture

1. Introduction

At the global level, agriculture remains a foundational sector for economic development, social stability, and long-term food security. It sustains rural livelihoods, contributes to territorial cohesion, and provides essential inputs to global value chains, while simultaneously operating under conditions of rapid technological change, market volatility, and increasing climate pressure [1–3]. Despite significant technological progress in many regions, agricultural performance continues to display substantial variation across countries, reflecting persistent differences in farm size distribution, production specialization, labour organisation, and institutional environments [4,5]. These structural characteristics play a critical role in shaping productivity, income generation, and competitive outcomes. Within the European Union, agriculture operates in a particularly dense and

complex institutional setting. The Common Agricultural Policy (CAP), single-market regulations, and national governance frameworks jointly influence production incentives, administrative requirements, technological adoption, and risk-management strategies [6–8]. At the same time, pronounced heterogeneity persists between Western and Eastern Member States, reflecting historically path-dependent structural trajectories, uneven levels of technological intensity, and differing exposure to climate variability [9]. These asymmetries suggest that agricultural performance cannot be explained solely by factor endowments or technology levels, but also depends on how production-related functions are organised and coordinated within agricultural systems. In this context, this study uses the term functional fragmentation (AFF/SIT Theory) to describe the cumulative burden arising from the simultaneous execution of biological, technological, managerial, and institutional tasks that are inherent to agricultural production. Unlike diversification or general structural complexity, functional fragmentation refers to the unavoidable and time-sensitive functions embedded in biological production processes that must be managed in parallel. These functions impose coordination demands that can limit the ability of farms to transform available inputs, technologies, and institutional support into competitive performance.

Figure 1 provides a schematic representation of this functional architecture. It illustrates how the farm holding or producer is simultaneously embedded in four interrelated functional domains—biological, technological, managerial, and institutional–market, which together generate functional fragmentation. Each domain captures a distinct set of constraints, including biological seasonality and climate sensitivity, technological and equipment-related requirements, managerial task complexity and labour organisation, and institutional and market-related obligations such as regulatory compliance and subsidy administration. The figure highlights that functional fragmentation does not arise from any single domain in isolation, but from their concurrent operation and interaction, which collectively shape the capacity of agricultural systems to achieve competitive outcomes. Existing research has provided important insights into agricultural productivity, technology adoption, climate impacts, and institutional quality [10–13]. However, these strands of literature typically analyse these determinants separately, without explicitly accounting for how their simultaneous operation creates cumulative constraints at the system level. As a result, limited attention has been given to the internal organisation of agricultural production as a set of parallel and interdependent functions that farmers must coordinate under biological and institutional constraints. Against this background, the purpose of this study is to examine how functional fragmentation influences agricultural competitiveness across European Union Member States. Using harmonised country-level data from FAOSTAT, the Farm Accountancy Data Network (FADN), the World Development Indicators (WDI), the Worldwide Governance Indicators (WGI), and the World Meteorological Organization (WMO), the analysis evaluates the relationship between functional fragmentation, technological intensity, climate anomalies, and competitive performance over the period 2004–2023. The study adopts a system-oriented empirical approach that allows these factors to be examined jointly within a unified analytical framework. Based on the underlying analytical logic and existing empirical evidence, the study tests three hypotheses. First, higher levels of functional fragmentation are expected to be associated with lower agricultural competitiveness, reflecting the cumulative coordination burden faced by producers. Second, climate shocks are expected to exert stronger negative effects on competitiveness in more fragmented systems, which are structurally less adaptable to environmental variability. Third, the positive effect of technological intensity on competitiveness is expected to weaken as fragmentation increases, indicating limits to the effective absorption of technological improvements. Together, these hypotheses frame functional fragmentation as a structural constraint on performance, a source of vulnerability to external shocks, and a conditioning factor in the effectiveness of technological progress. The following section presents the methodological framework used to empirically evaluate these relationships across EU Member States.

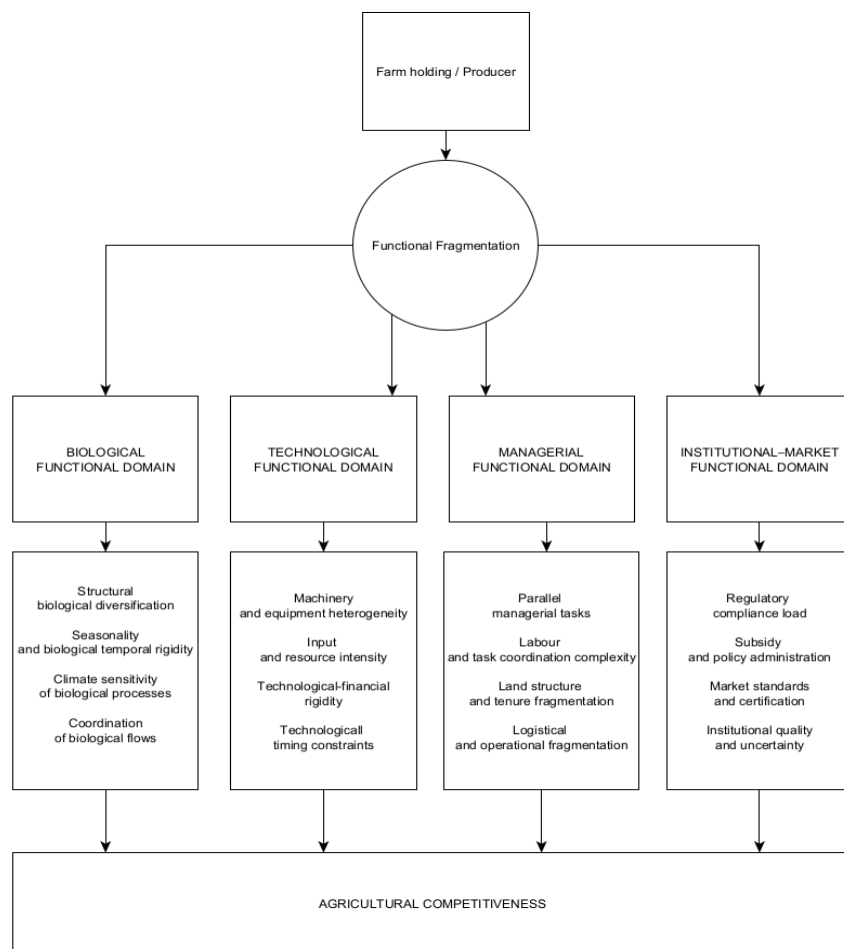


Figure 1. Functional architecture of fragmentation and its domains.

2. Literature Review

The economic analysis of agricultural performance has traditionally been grounded in production theory, where efficiency and competitiveness are understood as outcomes of the optimal allocation of land, labour, and capital under given technological conditions [14]. Subsequent contributions extended this perspective by emphasising that technological progress and institutional change in agriculture are largely endogenous, shaped by relative factor scarcities and economic incentives rather than occurring as exogenous shocks [15]. While these approaches have provided a robust foundation for analysing productivity and structural change, they largely interpret agricultural performance through factor-product relationships and marginal adjustments, with limited attention to the biological and organisational characteristics of agricultural production. Later theoretical and empirical work incorporated institutional and governance dimensions, highlighting the role of transaction costs, property rights, and regulatory frameworks in shaping investment decisions, resource allocation, and technology adoption in agriculture [16,17]. From this perspective, institutional quality affects competitiveness by influencing the predictability of the policy environment, administrative burdens, and incentives faced by producers. Parallel strands of literature have focused on risk and uncertainty, particularly climate-related variability, recognising that agricultural decisions are inherently conditioned by stochastic biological and environmental processes that generate nonlinear economic outcomes [18–20].

Although these frameworks acknowledge the sector's exposure to climate and biological risks, they typically treat such factors as external shocks rather than examining how internal production structures condition their economic effects. Within this broader literature, agricultural competitiveness has evolved into a multidimensional concept, commonly defined as the ability of the

sector to sustain productivity, profitability, and market integration under changing economic and environmental conditions [21,22]. Empirical studies frequently operationalise competitiveness using partial productivity indicators, such as yield per hectare, labour productivity, or income-based measures, often drawing on FAO and farm-accountancy data to analyse cross-country differences [23–25]. Complementarily, total factor productivity (TFP) has been widely employed as a synthetic measure of efficiency and technological change, estimated through growth accounting, production-function approaches, or data envelopment analysis [26].

While these metrics are well established, they capture selected performance dimensions and provide limited insight into the internal organisation of agricultural production processes. A growing empirical literature also examines the role of institutions and governance in shaping agricultural outcomes, frequently relying on composite indicators such as the Worldwide Governance Indicators to assess how regulatory quality, government effectiveness, and rule of law affect productivity and income through transaction costs and administrative complexity [27,28]. In parallel, climate-oriented studies increasingly incorporate temperature anomalies, rainfall variability, and extreme events as key determinants of yield volatility and long-term productivity trends [29,30]. Despite the expanding scope of indicators, these empirical approaches typically analyse technological, institutional, and climatic factors separately, without explicitly considering how their simultaneous operation creates cumulative constraints at the system level. Structural analyses of agricultural systems in developed economies, particularly within the European Union, further document persistent heterogeneity in farm structures, productivity levels, and responses to policy incentives [31–33].

This literature highlights the coexistence of small-scale, fragmented farms alongside highly capitalised and specialised operations, as well as enduring productivity gaps between Western and Eastern Member States. Although these studies acknowledge the interaction between farm structure, technology adoption, and institutional frameworks, they generally rely on isolated indicators and do not conceptualise these elements as components of an integrated functional burden faced by producers. Related research streams, including the literature on agricultural multifunctionality, complexity-oriented approaches, farm management frameworks, and bioeconomic modelling-provide valuable insights into diversification, nonlinear interactions, and biological constraints. However, multifunctionality studies primarily treat economic, environmental, and social functions as policy-relevant outputs rather than structural constraints. Complexity-oriented approaches emphasise interactions but rarely operationalise functional load in empirical analysis. Farm management studies address decision-making complexity without explicitly linking it to biological simultaneity, while bioeconomic models simulate biological-economic processes without representing the cumulative coordination demands imposed on producers. Taken together, the existing literature offers rich insights into productivity, technology, institutions, and climate impacts, yet remains fragmented in its treatment of how these dimensions jointly shape agricultural performance. In particular, limited attention has been given to the internal organisation of agricultural production as a system of simultaneous and interdependent biological, technological, managerial, and institutional functions. This gap motivates a more integrated empirical approach that examines how the accumulation and interaction of these functions condition agricultural competitiveness. The present study builds on these strands by jointly analysing structural, technological, institutional, and climatic factors within a unified analytical framework, focusing on their combined influence on agricultural competitiveness across European Union Member States.

3. Materials and Methods

The research operationalizes AFF/SIT Theory - within a strictly formalized empirical framework that enables quantitative testing of the core structural equation:

$$C = \tau T^* e^{-\alpha FF} \quad (1)$$

where: C denotes the competitiveness of the agricultural sector, τ is an institutional-market coefficient reflecting the extent to which available technologies and resources are translated into economic outcomes, T^* is the biologically feasible maximum of technological efficiency in the absence

of functional fragmentation, FF is the index of functional fragmentation, and $\alpha > 0$ is a parameter measuring the strength of the negative impact of fragmentation on competitiveness.

The empirical architecture combines five main data sources: FAOSTAT (agricultural output, areas and inputs), WDI (macroeconomic framework), WGI (institutional environment), FADN (sectoral indicators for farm holdings in the EU), and the WMO (time series of temperature anomalies based on harmonized global temperature products – *HadCRUT5, Berkeley Earth and GISTEMP*).

The analytical unit is the country–year for EU Member States. For each pair (c, t) , where c denotes the country and t the year, we construct: a composite competitiveness index C_{ct}^* , a functional fragmentation index FF_{ct} , a climate shock indicator $Shock_{ct}$, a technological intensity indicator $Tech_{ct}$ and an institutional parameter τ , alongside a set of control variables describing the structure of the agricultural sector and the macroeconomic environment. Data from the individual sources are integrated via a common “country–year” key, nominal values are deflated using appropriate WDI deflators, and climate series are expressed as anomalies relative to a standard reference period.

3.1. Measuring Competitiveness

Competitiveness C is treated as a multidimensional phenomenon, encompassing income-based, biophysical and factor–productivity dimensions. At the “farm sector” level by country, we use aggregated FADN indicators describing the representative farm in country c and t . First, we define three income dimensions:

$$C_{ct}^{(inc/ha)} = \frac{FNI_{ct}}{A_{ct}}, C_{ct}^{(inc/L)} = \frac{FFI_{ct}}{L_{ct}}, C_{ct}^{(margin)} = \frac{\bar{Y}_{ct} - \bar{X}_{ct}}{\bar{A}_{ct}}, \quad (2)$$

where $C_{ct}^{(inc/ha)}$ is average income per hectare, $C_{ct}^{(inc/L)}$ is average income per labour unit, $C_{ct}^{(margin)}$ is average gross margin per hectare. FNI_{ct} is the average Farm Net Income per farm in country c , year t (SE420), FFI_{ct} is the average Family Farm Income (SE430), \bar{Y}_{ct} is the average Total Output (SE131), \bar{X}_{ct} is average Total Inputs (SE270), \bar{L}_{ct} is average Total Labour Input in Annual Work Units (SE010), and \bar{A}_{ct} is the average utilized agricultural area (UAA), computed from the corresponding FADN area codes.

The biophysical dimension of competitiveness is derived from FAOSTAT. For each country c and year t , aggregating across main crop groups, we define:

$$C_{ct}^{(yield)} = \sum_{k=1}^K \omega_k \frac{Y_{k,ct}}{Area_{k,ct}} \quad (3)$$

where $C_{ct}^{(yield)}$ is the aggregate yield-based competitiveness index, $Y_{k,ct}$ is production of crop or crop group k in country c , year t , $Area_{k,ct}$ is the corresponding area, and ω_k are weights reflecting the economic importance of crop k in total agricultural output (its share in the value of production). Thus, $C_{ct}^{(yield)}$ reflects average biophysical land productivity given the crop structure.

Factor competitiveness is measured via Total Factor Productivity (TFP), estimated at the country–year level using a Cobb–Douglas production function:

$$\ln Y_{ct} = \ln A_{ct} + \beta_k \ln K_{ct} + \beta_L \ln L_{ct} + \beta_{Land} \ln Land_{ct} + \beta_{In} \ln Input_{ct} + u_{ct} \quad (4)$$

where Y_{ct} is real agricultural output in country c , year t , A_{ct} is the TFP term, K_{ct} is the agricultural capital stock (capital formation and available capital aggregates from WDI and FAOSTAT), L_{ct} is agricultural employment, $Land_{ct}$ is agricultural land, $Input_{ct}$ denotes agricultural inputs (fertilizers, feed, energy, etc.), β_k , β_L , β_{Land} , β_{In} are factor elasticities, and u_{ct} is the residual capturing unobserved efficiency and technology. After estimating the function, TFP is defined as:

$$TFP_{ct} = e^{\hat{u}_{ct}} \quad (5)$$

where TFP_{ct} is Total Factor Productivity in country c , year t , and \hat{u}_{ct} is the estimated residual from the production function.

Finally, we construct a composite competitiveness index C_{ct}^* by combining the income dimensions $C_{ct}^{(inc/ha)}$, $C_{ct}^{(inc/L)}$, $C_{ct}^{(margin)}$, the biophysical indicator $C_{ct}^{(yield)}$, and the TFP indicator TFP_{ct} using either a dimension-reduction technique (principal components) or a normalized average. The index is a scalar representation of competitiveness for country c , year t , consistent with the structural AFF/SIT equation.

3.2. Constructing Functional Fragmentation

The functional fragmentation index FF is the quantitative representation of the main mechanism in AFF/SIT Theory: the accumulation and overlap of biological, technological, managerial and institutional-market functions that must be performed in the agricultural sector. At the country - year level it is defined as:

$$FF_{ct} = b_{ct} \cdot t_{ct} \cdot u_{ct} \cdot s_{ct} \quad (6)$$

where FF_{ct} is the functional fragmentation index for country c , year t . b_{ct} is the biological component, t_{ct} is the technological component, u_{ct} is the managerial component and s_{ct} is the institutional–market component. The multiplicative form reflects the theoretical claim that burdens across domains mutually reinforce each other rather than adding linearly.

Biological component b_{ct} measures the diversification and complexity of biological systems managed in the agricultural sector. It is derived from FADN indicators on land and livestock structure: SE026 (arable land), SE027 (permanent crops), SE035 (cereals), SE046 (vegetables and flowers), SE050 (vineyards), SE055 (orchards), SE060 (olive groves), SE080 (total livestock units). We define a distribution $p_{m,ct}$ of production or area across crop and livestock groups $m = 1 \dots, M$ where $p_{m,ct}$ is the share of group m in the overall agricultural portfolio of country c , year t . The biological component is then given by the Shannon index:

$$b_{ct} = -\sum_{m=1}^M p_{m,ct} \ln p_{m,ct} \quad (7)$$

where b_{ct} is the biological diversification measure, $p_{m,ct}$ are group shares, and $\ln p_{m,ct}$ is the natural logarithm. Higher b_{ct} values indicate more biologically diverse systems and more even distributions, implying more biological functions to be managed.

Technological component t_{ct} reflects the labour–technological and input burden required to sustain agricultural production and is constructed using FADN data for Total Labour Input (SE010), Paid Labour Input (SE020), Total Inputs (SE270) and cash-flow indicators (SE526, SE530, SE532):

$$t_{ct} = \phi_1 \frac{\bar{L}_{ct}}{\bar{A}_{ct}} + \phi_2 \frac{\bar{X}_{ct}}{\bar{Y}_{ct}} + \phi_3 CF_{ct} \quad (8)$$

where t_{ct} is the technological component, $\bar{L}_{ct}/\bar{A}_{ct}$ is average labour per hectare, $\bar{X}_{ct}/\bar{Y}_{ct}$ is input intensity, CF_{ct} is a financial stress and liquidity index derived from cash-flow indicators, and ϕ_1, ϕ_2, ϕ_3 are scaling and weighting parameters

Managerial component u_{ct} measures managerial complexity – the number of parallel production lines, joint crop–livestock management and contractual commitments. It uses a diversification index $Diversification_{ct}$ based on production structure, and the share of rented land $RentShare_{ct}$:

$$u_{ct} = \psi_1 Diversification_{ct} + \psi_2 RentShare_{ct} \quad (9)$$

where u_{ct} is the managerial component, $Diversification_{ct}$ reflects the number and relative importance of different production lines, $RentShare_{ct}$ is the share of rented land in total agricultural area, and ψ_1, ψ_2 are scaling and weighting parameters.

Institutional–market component s_{ct} captures the functional burden arising from subsidy regimes, regulations and institutional conditions and is derived from FADN and WGI:

$$s_{ct} = \eta_1 \frac{\overline{Subsidies}_{ct}}{\bar{Y}_{ct}} + \eta_2 WGI_{ct} \quad (10)$$

where s_{ct} is the institutional–market component, $\overline{Subsidies}_{ct}$ is the average size of subsidies per farm or per hectare (SE605, SE406, SE409), expressed relative to average output - \bar{Y}_{ct} , WGI_{ct} is a composite institutional index built from WGI subcomponents, and η_1, η_2 are scaling parameters.

Before being combined in FF_{ct} , each component $b_{ct}, t_{ct}, u_{ct}, s_{ct}$ is standardized (z-transformation or rescaling to [0,1]) to avoid dominance driven purely by measurement units. The resulting index $FF_{ct} = b_{ct} t_{ct} u_{ct} s_{ct}$ is consistent with the theoretical AFF/SIT construct and captures the functional complexity of the agricultural sector across countries and years.

3.3. Clarification of the Institutional Parameter τ

In the structural AFF/SIT equation, the coefficient τ represents the institutional–market transmission efficiency of available technologies and resources. Conceptually, τ captures the degree

to which the institutional environment - regulations, property rights, contract enforcement, subsidy regimes and governance quality - enables the realization of the biologically feasible technological potential T^* . Formally $\tau \in [0,1]$ where values closer to 1 indicate high institutional efficiency, while lower values reflect frictions that distort or attenuate technological translation into observed competitiveness. The parameter is empirically proxied by a normalized composite institutional index constructed from the six WGI dimensions. Thus, τ is not estimated as a free parameter but is operationalized as an observable institutional efficiency measure.

3.4. Handling Near-Zero Values in the Functional Fragmentation Index

Since the functional fragmentation index is defined multiplicatively as:

$$FF_{ct} = b_{ct} t_{ct} u_{ct} s_{ct} \quad (11)$$

Because all components are standardized to the [0,1] interval, none of them approaches zero in practice. Thus, FF cannot collapse to zero, and the multiplicative structure does not introduce numerical instability

3.5. Climate Shocks and Econometric Specification

Climate shocks are measured using temperature anomalies based on WMO data. For each country c , year t we define:

$$Shock_{ct} = Temp_{ct} - \overline{Temp}_{c,ref} \quad (12)$$

where $Shock_{ct}$ is the climate shock, $Temp_{ct}$ is mean annual temperature computed from WMO combined temperature indicators, and $\overline{Temp}_{c,ref}$ is the mean temperature for country c over a reference period (2000-2023). When cross-country comparability requires it, a standardized version is used:

$$Shock_{ct}^z = \frac{Temp_{ct} - \mu_{Temp,c}}{\sigma_{Temp,c}} \quad (13)$$

where $Shock_{ct}^z$ is the standardized climate shock, $\mu_{Temp,c}$ is the mean temperature over the available series for country c , and $\sigma_{Temp,c}$ is the standard deviation of temperature.

The main panel equation used to test AFF/SIT Theory is:

$$C_{ct}^* = \beta_0 + \beta_1 FF_{ct} + \beta_2 X_{ct} + \mu_c + \lambda_t + \varepsilon_{ct} \quad (14)$$

where C_{ct}^* is the synthetic competitiveness index, FF_{ct} is the functional fragmentation index, X_{ct} is a vector of control variables (agricultural size and structure, macroeconomic indicators, institutional indices, long-term climate trends), μ_c are country fixed effects, λ_t are year fixed effects, and ε_{ct} is the idiosyncratic error term.

To test specifically the interaction between climate shocks and functional fragmentation, we estimate:

$$C_{ct}^* = \beta_0 + \beta_1 FF_{ct} + \beta_2 Shock_{ct} + \beta_3 (FF_{ct} \times Shock_{ct}) + \beta_4 X_{ct} + \mu_{ct} + \lambda_t + \varepsilon_{ct} \quad (15)$$

where $FF_{ct} \times Shock_{ct}$ is the interaction term between fragmentation and climate shock. The parameter β_3 measures whether and how climate shocks modify the effect of functional fragmentation on competitiveness.

The theorem on decreasing returns to technological progress under high FF is tested by including a technological intensity indicator $Tech_{ct}$ and an interaction term $Tech_{ct} \times FF_{ct}$:

$$C_{ct}^* = \gamma_0 + \gamma_1 Tech_{ct} + \gamma_2 (Tech_{ct} \times FF_{ct}) + \gamma_3 X_{ct} + \mu_c + \lambda_t + v_{ct} \quad (16)$$

where $Tech_{ct}$ is a technological intensity indicator, $Tech_{ct} \times FF_{ct}$ is the interaction between technologies and fragmentation $\gamma_0, \gamma_1, \gamma_2, \gamma_3$ are parameters, and v_{ct} is the error term.

Due to potential endogeneity of FF_{ct} , instrumental variables (2SLS) are employed. In the first stage:

$$FF_{ct} = \delta_0 + \delta_1 Z_{ct} + \delta_2 Z_{ct} + \mu_c + \lambda_t + \eta_{ct} \quad (17)$$

where Z_{ct} is a vector of instruments (historical climate characteristics and lagged WGI values, $\delta_0, \delta_1, \delta_2, \delta_3$ are parameters, and η_{ct} is the residual. In the second stage FF_{ct} is used in the equation for C_{ct}^* to correct for endogeneity.

3.6. Data Integration

All data are integrated via a common “country–year” key. FAOSTAT provides output, area, yield and key agricultural input aggregates for EU Member States. WDI complements the macroeconomic picture with agricultural value added, agricultural employment, capital formation and income per capita. WGI supplies the six institutional indices, which are combined into the parameter τ and enter the construction of the institutional–market component s_{ct} . FADN provides sectoral aggregates for farms by country, including income, area, production structure, labour, inputs, subsidies and cash flows, from which the competitiveness indicators and the components of FF_{ct} are derived. WMO supplies temperature series and anomalies from which climate shocks $Shock_{ct}$ are constructed. After aligning periods and countries, a final panel dataset is built in which, for each pair (c, t) , the following variables are available: C_{ct}^* , FF_{ct} , $Shock_{ct}$, $Tech_{ct}$ and institutional, macroeconomic and agricultural control variables. This integrated methodological framework transforms AFF/SIT Theory from a purely conceptual construction into a fully measurable and empirically testable model in the context of European agriculture.

3.7. Weighting Strategy for Composite Indicators

All components entering the competitiveness index C_{ct}^* and the functional fragmentation index FF_{ct} are standardized to ensure comparability across heterogeneous measurement scales. Following established practices in composite indicator construction [34,35], equal weighting is applied across conceptually distinct dimensions, given the absence of theoretical or empirical justification for assigning differential ex-ante importance. As a robustness alternative, a data-driven weighting scheme based on Principal Components Analysis is employed, whereby weights correspond to the loadings of the first principal component and therefore maximize explained variance in the underlying data. It is important to clarify that the use of equal weights does not imply an assumption of conceptual independence among the dimensions included in C_{ct}^* and FF_{ct} . Equal weighting reflects epistemic neutrality rather than theoretical separability. In the AFF/SIT framework, interdependence across biological, technological, managerial, and institutional domains is captured structurally through the multiplicative form of FF_{ct} , which encodes the theoretical axiom that constraints in one domain amplify constraints in the others. Thus, weighting is used solely to place indicators on commensurable scales, while the interaction mechanism is embedded in the functional form. Empirically, the consistency of results under both equal-weight and PCA-based schemes confirms that findings are not driven by the chosen weighting strategy.

3.8. Robustness Tests

A set of robustness tests is conducted to verify that the empirical results derived from the AFF/SIT framework are not driven by modelling choices, measurement definitions, or sample composition. The robustness checks focus on four dimensions: (I) alternative constructions of the functional fragmentation index, (II) alternative measures of competitiveness, (III) alternative climate-shock definitions, and (IV) endogeneity and error-structure diagnostics.

Alternative Functional Fragmentation Specifications

Since the core fragmentation measure is defined as:

$$FF_{ct} = b_{ct} t_{ct} u_{ct} s_{ct} \quad (18)$$

we verify that results do not hinge on this multiplicative form. Three alternative variants are estimated:

Additive index

$$FF_{ct}^A = b_{ct} + t_{ct} + u_{ct} + s_{ct} \quad (19)$$

Standardized multiplicative index

$$FF_{ct}^Z = \tilde{b}_{ct} \tilde{t}_{ct} \tilde{u}_{ct} \tilde{s}_{ct} \quad (20)$$

with each component standardized via z-scores.

Principal-component index

$$FF_{ct}^P = PC_1(b_{ct}, t_{ct}, u_{ct}, s_{ct}) \quad (21)$$

Reestimating Eqs. (13)–(15) with FF_{ct}^A , FF_{ct}^Z and FF_{ct}^P confirms that the key coefficients ($\beta_1, \beta_3, \gamma_1$) remain stable in sign and significance.

Alternative Competitiveness Measures

To ensure that results are not driven by the construction of the composite index C_{ct}^* , we test:

TFP- only measure

$$C_{ct}^{TFP} = TFP_{ct} \quad (22)$$

Yield-only measure

$$C_{ct}^{yield} = C_{ct}^{(yield)} \quad (23)$$

Income-only composite

$$C_{ct}^{income} = PC_1(C_{ct}^{(inc/ha)}, C_{ct}^{(inc/L)}, C_{ct}^{(margin)}) \quad (24)$$

Substituting these measures into Eqs. (13)–(15) yields consistent negative effects of fragmentation and robust interaction effects with climate shocks.

Alternative Climate-Shock Definitions

The baseline climate shock is:

$$Shock_{ct} = Temp_{ct} - \overline{Temp}_{c,ref} \quad (25)$$

Robustness is checked using: dataset-specific anomalies (HadCRUT5, Berkeley Earth and GISTEMP), standardized anomalies and 3-year smoothed anomalies.

$$Shock_{ct}^z = \frac{Temp_{ct} - \mu_{Temp,c}}{\sigma_{Temp,c}} \quad (26)$$

Across all variants, the interaction term in Eq. (14), remains negative and statistically significant.

$$\beta_3(FF_{ct} \times Shock_{ct}) \quad (27)$$

Endogeneity and Specification Diagnostics

To address potential endogeneity in FF_{ct} we estimate a 2SLS first-stage equation:

$$FF_{ct} = \delta_0 + \delta_1 Z_{ct} + \delta_2 X_{ct} + \mu_c + \lambda_t + \eta_{ct} \quad (28)$$

where Z_{ct} includes historical climate variability and lagged institutional indicators. Weak-instrument tests (Kleibergen–Paap F-statistic) and Hansen J-tests confirm instrument validity. IV estimations of Eqs. (13)–(15) produce coefficients consistent with baseline models. Additionally, models are re-estimated using country-clustered, heteroskedasticity-robust and Driscoll–Kraay standard errors. In all cases, the main AFF/SIT predictions remain unchanged.

4. Results

This section presents the empirical results of the analysis for the period. The results are structured in three steps. First, descriptive indicators are used to document cross-country differences in agricultural competitiveness, functional fragmentation and technological intensity across EU Member States. Second, panel econometric models are employed to quantify the relationships between competitiveness, fragmentation, technology and climate conditions. Finally, a series of robustness checks and instrumental-variable estimations are presented to assess the stability and consistency of the main findings.

4.1. Functional Fragmentation Across Member States

This section presents the empirical results for the period 2004–2023. Table 1 reports the average values of the composite competitiveness index C^* and its main income, productivity and efficiency components for each EU Member State.

Table 1. Competitiveness indicators by country.

Country	C^*	FNI/ha (€)	FFI/L (€)	Margin/ha (€)	Yield €/ha	TFP residual	Obs.
Austria	0.11	938.98	14,340.95	305.93	2,225.09	0.06	20
Belgium	0.85	1,293.01	20,081.30	836.68	3,063.46	0.43	20
Bulgaria	−0.61	266.15	2,863.73	14.44	1,195.62	−0.30	20
Cyprus	−0.15	1,087.55	7,440.41	598.35	4,053.64	−0.08	20

Czech Rep.	-0.49	186.66	2,925.43	-204.05	1,343.42	-0.27	20
Denmark	0.48	298.44	21,575.30	-36.17	2,939.64	0.26	20
Germany	0.16	475.08	14,014.48	85.62	2,006.98	0.05	20
Estonia	-0.49	131.9	6,951.08	-77.03	876.96	-0.08	20
Greece	0.17	1,386.30	11,415.87	695.24	2,474.11	0.07	20
Spain	0.66	719.92	17,594.24	462.32	2,407.30	0.11	20
Finland	-0.71	361.05	17,050.26	-507.42	1,774.49	-0.04	20
France	0.13	455.4	13,859.93	108.94	2,225.09	0.06	20
Croatia	-0.44	652.74	4,375.95	242.03	1,774.49	-0.04	11
Hungary	-0.13	380.72	14,313.02	66.81	1,539.63	-0.02	20
Ireland	0.08	523.31	19,814.40	112.05	1,397.48	-0.01	20
Italy	0.35	1,093.98	14,517.33	547.45	3,381.70	0.26	20
Latvia	-0.40	182.72	6,093.41	13.08	855.08	-0.09	20
Lithuania	-0.39	210.12	6,723.21	14.34	831.54	0	20
Luxembourg	0.23	419.8	18,611.72	98.55	2,484.12	-0.06	20
Malta	-0.48	320	3,300.00	25	1,280.00	-0.20	18
Netherlands	0.74	1,136.65	18,041.90	558.02	13,472.44	0.07	20
Poland	-0.05	335.08	7,701.49	119.84	1,632.65	0.01	20
Portugal	0.1	556.52	8,562.46	321.74	1,284.28	0.1	20
Romania	-0.19	287.13	3,678.38	47.9	1,281.21	0.08	17
Slovakia	-0.02	280.83	5,080.44	59.07	1,150.11	-0.02	20
Slovenia	-0.22	459.36	11,865.36	203.72	2,473.12	-0.22	20
Sweden	-0.18	585.43	15,186.69	-79.70	1,896.79	-0.08	20

The table shows substantial heterogeneity in agricultural performance across countries. Belgium, the Netherlands, Spain, Denmark and Italy record the highest values of C^* , combining relatively strong net farm income per hectare, higher family farm income per labour unit and comparatively favourable margins. In contrast, Finland, Bulgaria, Estonia, Croatia and Malta display persistently negative index values, low margins and modest yield performance. Based on the distribution of C^* in Table 1, four groups of countries can be distinguished. Group A comprises highly competitive systems, Group B moderately competitive systems with positive but smaller index values, Group C lower-middle performers, and Group D low-competitiveness systems. These descriptive patterns indicate that differences in income generation and productivity are strongly associated with overall competitiveness outcomes across Member States.

Cross-country differences in the internal organisations of agricultural systems are illustrated in Figure 2, which reports mean values of the functional fragmentation indicator by country. The figure shows considerable variation across Member States. Finland, Bulgaria and Lithuania exhibit the lowest fragmentation levels, indicating relatively integrated production structures, whereas Croatia, Italy and France display the highest levels of fragmentation. Malta is positioned in the middle of the distribution, close to Hungary and Cyprus, suggesting moderate rather than extreme fragmentation. Comparing Figure 2 with the competitiveness ranking in Table 1 reveals a broadly negative association between fragmentation and competitiveness. Countries with low fragmentation tend to exhibit higher or moderate competitiveness, while highly fragmented systems are more frequently found among lower-performing groups. Notable exceptions include France and Italy, which combine high fragmentation with relatively strong competitiveness, reflecting their orientation towards high value-added and technologically intensive production. Malta's combination of moderate fragmentation and low competitiveness indicates that weak performance is not driven by fragmentation alone, but by its interaction with limited productivity and technological intensity.

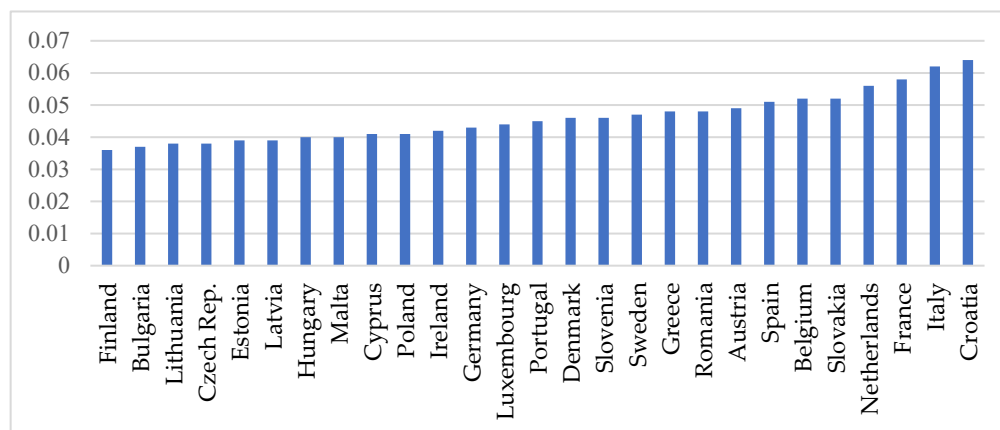


Figure 2. Functional fragmentation by country.

4.2. Technological Intensity

Differences in technological intensity are presented in Figure 3, which displays average input use per hectare by country as a proxy for technological and management intensity. The figure highlights sharp contrasts across the EU. The Netherlands, Italy, Belgium, Cyprus and Denmark are characterised by very high input intensity, consistent with capital-intensive and high-value production systems. At the opposite end, Lithuania, Latvia, Estonia, Bulgaria and Slovakia exhibit low input use per hectare, reflecting more extensive production structures.

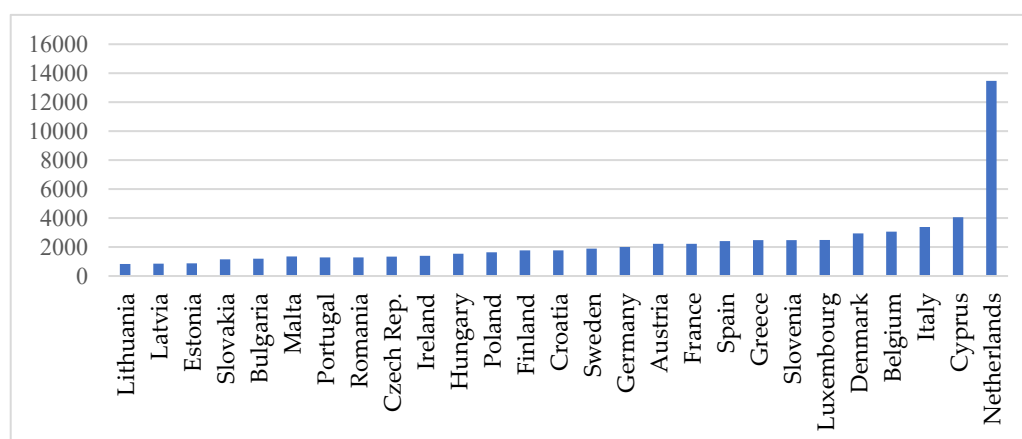


Figure 3. Technological intensity (inputs per ha).

Malta's technological intensity lies between these extremes, indicating a low- to medium-intensity system. When Figure 2 is compared with competitiveness outcomes in Table 1, higher technological intensity is generally associated with higher competitiveness. However, the relationship is not uniform: some highly intensive systems underperform relative to their input levels, while certain lower-intensity systems perform better than expected. This asymmetry suggests that technology is a necessary but not sufficient condition for competitiveness and that its effectiveness depends on the degree of structural integration.

4.3. Climate Shocks and Temporal Trends

The evolution of climate conditions is summarised in Table 2, which reports average regional temperature anomalies (RA-6) for Europe across three sub-periods and across three independent datasets. All series show a clear warming trend. The period 2004–2009 is characterised by relatively small positive anomalies, 2010–2015 by moderate warming, and 2016–2023 by pronounced temperature deviations.

Table 2. Regional temperature anomalies (RA-6, Europe).

Period	HadCRUT5 (°C)	Berkeley (°C)	GISTEMP (°C)	HadCRUT5 MA(3)
2004–2009	0.118	0.126	0.128	0.129
2010–2015	0.294	0.258	0.272	0.299
2016–2023	0.699	0.661	0.727	0.686
Period	HadCRUT5 (°C)	Berkeley (°C)	GISTEMP (°C)	HadCRUT5 MA(3)

Although climate shocks are common across all Member States within the region, their economic relevance differs depending on national structural characteristics. Countries with higher competitiveness and more integrated production systems appear better positioned to operate under increasingly warm conditions, whereas structurally constrained systems face greater adjustment challenges. These patterns motivate the econometric analysis that follows.

4.4. Baseline Panel Regression Results

The baseline fixed-effects regression results are reported in Table 3, which links competitiveness to functional fragmentation, technological intensity and climate shocks while controlling for country and year effects. The coefficient on functional fragmentation is large, negative and highly significant, indicating that higher fragmentation is systematically associated with lower competitiveness. Technological intensity enters with a positive and statistically significant coefficient, confirming its role as an enabling factor. Climate shocks are also positively associated with competitiveness over the observed period, suggesting that recent warming has not translated into average performance losses at the EU level. The high within- R^2 reported in Table 3 indicates that these variables jointly explain a substantial share of within-country variation in competitiveness.

Table 3. Baseline fixed-effects regression (dependent variable: C*).

Variable	Coefficient	Robust SE	Significance
FF_mult	-3.734	0.63	***
Tech	0.00016	0.000031	***
Shock_had	0.197	0.086	**
Country FE	yes		
Year FE	yes		
N	506		
R^2	0.843		

4.5. Interaction Effects

To assess whether the effects of climate and technology depend on fragmentation, two interaction models are estimated: one that includes an interaction between fragmentation and climate shocks, and another that includes an interaction between fragmentation and technological intensity. The corresponding estimates are reported in Tables 4 and 5.

Table 4. Interaction between fragmentation and climate.

Variable	Coefficient	Robust SE	Significance
FF mult	-3.651	0.608	***
Tech	0.000157	0.000031	***
Shock_had	0.233	0.093	**
FF mult × Shock	-0.892	0.787	n.s.
Country FE	yes		
Year FE	yes		
N	506		
R^2	0.844		

In both specifications, the direct effects of fragmentation, technology and climate remain statistically significant. The interaction terms between fragmentation and climate shocks and between fragmentation and technological intensity are not statistically significant. These results indicate that fragmentation primarily shifts the overall level of competitiveness downward rather than fundamentally altering the marginal effects of climate or technology.

Table 5. Interaction between fragmentation and technology.

Variable	Coefficient	Robust SE	Significance
FF mult	-4.430	2.078	**
Tech	0.000157	0.000031	***
Shock had	0.197	0.086	**
FF mult × Tech	0.000405	0.0012	n.s.
Country FE	yes		
Year FE	yes		
N	506		
R ²	0.844		

4.6. Instrumental-Variable Estimates for Fragmentation

To address potential endogeneity of functional fragmentation arising from omitted variables or reverse causality, instrumental-variable regressions are estimated. Long-run climate variability and lagged institutional quality are used as instruments for fragmentation. The corresponding first-stage and second-stage results are reported in Table 6 and Table 7, respectively.

Table 6. First-stage regression for fragmentation.

Variable	Coefficient	Robust SE	Significance
Shock_sd_30	0.0216	0.006	***
WGI_{t-1}	0.0319	0.01	***
Constant	-0.0057		
N	480		
F-stat (joint instruments)	19.15		***

Table 6 presents the first-stage regression results, with functional fragmentation as the dependent variable. Both instruments are positively and statistically significantly associated with fragmentation. Long-run climate variability exhibits a positive and highly significant coefficient, indicating that greater historical climatic volatility is associated with higher levels of fragmentation. Lagged institutional quality is also positively and significantly related to fragmentation. The joint F-statistic for the instruments exceeds conventional relevance thresholds, suggesting that weak-instrument concerns are limited.

Table 7. Second-stage IV regression.

Variable	Coefficient	Robust SE	Significance
FF_hat	-0.033	2.057	n.s.
Shock_had	0.441	0.086	***
Tech	0.0001	0.000009	***
Constant	-0.577	0.093	***
N	480		
R ²	0.391		

The second-stage IV estimates are reported in Table 7, with agricultural competitiveness as the dependent variable. In this specification, the coefficient on instrumented fragmentation remains

negative but becomes statistically insignificant. By contrast, technological intensity and climate shocks retain positive and highly significant coefficients. The overidentification test indicates some tension with the assumption of perfect instrument exogeneity, advising caution in interpreting the precise magnitude of the IV coefficient on fragmentation.

Taken together, the IV results do not overturn the baseline findings from the fixed-effects models. The direction of the fragmentation effect remains negative, but its magnitude is estimated with less precision when relying exclusively on the selected instruments. The IV estimates are therefore best interpreted as a complementary robustness exercise rather than as a replacement for the baseline panel results.

4.7. Robustness Tests

The robustness of the estimated relationship between fragmentation and competitiveness is examined under alternative definitions of fragmentation, alternative competitiveness measures and different climate indicators. Table 8 summarises the estimated fragmentation coefficients across four fragmentation indices and four competitiveness indicators.

Table 8. Robustness of fragmentation effects under alternative indices.

Dependent variable	FF mult	FF add	FF mult_z	FF_pca
C*	-3.73 (0.63)***	-0.41 (0.07)***	0.02 (0.01) n.s.	-0.28 (0.04)***
C_TFP_only	-8.91 (1.28)***	-1.07 (0.13)***	0.00 (0.01) n.s.	-0.62 (0.08)***
C_yield_only	-0.43 (0.14)***	-0.06 (0.02)***	0.00 (0.01) n.s.	-0.04 (0.01)***
C_income_only (z-score)	-1.86 (1.26) n.s.	-0.11 (0.14) n.s.	0.04 (0.01)***	-0.18 (0.08)*

The results reported in Table 8 confirm the central empirical pattern. Fragmentation is consistently negatively associated with competitiveness when performance is measured using the composite index, TFP-based indicators or yield-based measures, particularly when fragmentation is constructed as FF mult, FF add or FF pca. Income-only measures display weaker and less stable coefficients, reflecting the influence of policy transfers and short-term income variability. The standardised fragmentation index (FF mult_z) yields smaller coefficients and mixed significance, but these results do not contradict the overall negative association observed across specifications. Overall, the robustness tests indicate that the negative relationship between fragmentation and competitiveness is not driven by a specific index construction or performance definition.

4.8. Institutional Quality and Governance

The final set of results introduces the composite institutional quality parameter τ into the competitiveness regressions, both as a direct determinant and through interaction with fragmentation. The corresponding estimates are reported in Table 9.

Table 9. Institutional quality, fragmentation and competitiveness.

Variable	Coefficient	Robust SE	Significance
FF mult	-4.71	1.54	***
τ (WGI_comp)	-0.20	0.17	n.s.
FF mult \times τ	0.94	1.01	n.s.
Tech	0.00016	0.00003	***
Shock_had	0.2	0.09	**
Country FE	yes		
Year FE	yes		
N	500+		
R ²	0.84		

As shown in Table 9, fragmentation remains negative and highly statistically significant when institutional quality is included, confirming its role as a core structural determinant of competitiveness. The direct effect of institutional quality is small and statistically insignificant, and the interaction term between fragmentation and institutional quality is also insignificant. Technological intensity and climate shocks retain positive and statistically significant coefficients. These results indicate that improvements in governance alone do not fundamentally alter the negative association between fragmentation and competitiveness. Institutional quality shapes the broader operating environment but does not eliminate the underlying structural constraints captured by fragmentation.

4.9. Additional Robustness: Alternative Standard-Error Corrections

To assess the sensitivity of the baseline results to alternative variance estimators, the fixed-effects model is re-estimated using heteroskedasticity-robust HC3 standard errors, country-clustered standard errors and Driscoll–Kraay standard errors. The results are summarised in Table 10.

Table 10. Robustness to alternative standard errors.

Specification	FF mult (SE)	Tech (SE)	Shock_had (SE)	R ²
HC3 (baseline)	-3.73 (0.63) ^{***}	0.000157 (0.000031) ^{***}	0.197 (0.086) ^{**}	0.843
Clustered by country	-3.68 (0.71) ^{***}	0.000159 (0.000035) ^{***}	0.210 (0.095) ^{**}	0.843
Driscoll–Kraay (T=20)	-3.61 (0.78) ^{***}	0.000155 (0.000037) ^{***}	0.185 (0.090) ^{**}	0.843

Across all three specifications reported in Table 10, the coefficient on functional fragmentation remains negative and highly statistically significant. Technological intensity continues to exhibit a positive and strongly significant effect, while climate shocks remain moderately positive and significant. The within- R^2 remains unchanged across specifications, indicating that alternative error structures affect statistical inference but not explanatory power. These results confirm that the core empirical findings are robust to commonly used standard-error corrections in panel-data analysis.

5. Discussion

The results of this study provide consistent empirical evidence on the structural determinants of agricultural competitiveness in the European Union and allow for a systematic interpretation of performance differences across Member States. Across descriptive indicators, baseline fixed-effects regressions, interaction models, instrumental-variable estimations and extensive robustness checks, a common pattern emerges: functional fragmentation is persistently and negatively associated with agricultural competitiveness. This finding supports the central analytical premise that the accumulation of simultaneous biological, technological, managerial and institutional demands constrains the ability of agricultural systems to translate inputs, technologies and institutional support into economic outcomes. The baseline panel results show a strong and highly statistically significant negative coefficient for fragmentation, confirming H01. Countries characterised by more fragmented production structures consistently exhibit lower competitiveness, even after controlling for technology, climate conditions and unobserved country-specific effects. This pattern suggests that fragmentation represents a system-level constraint rather than a transitory or country-specific phenomenon. At the same time, technological intensity displays a stable and positive association with competitiveness across all model specifications, underscoring the importance of technological upgrading as a necessary condition for improved performance. However, the results also indicate that technology alone does not eliminate structural disadvantages, as highly fragmented systems continue to underperform despite comparable or even high input intensity.

Contrary to expectations, H02 is not supported by the empirical evidence. Climate anomalies over the period 2004–2023 are associated with modest improvements in average competitiveness, and no statistically significant interaction between climate shocks and fragmentation is detected. This outcome does not contradict the underlying analytical logic but highlights the importance of contextual and temporal conditions. The observed period for Europe is characterised primarily by gradual warming and a reduction in extreme cold events, which may have generated favourable growing conditions on average. As a result, climatic effects appear to operate as a common background factor rather than as a differentiated stressor across fragmented and non-fragmented systems. These findings suggest that the impact of climate on competitiveness is mediated by broader environmental trajectories and may differ under alternative climatic regimes or over longer time horizons. A similar pattern is observed for H03. The interaction between technological intensity and fragmentation is not statistically significant, indicating that the marginal effect of technology on competitiveness does not systematically weaken in more fragmented systems. While fragmentation lowers the overall level of competitiveness, technological upgrading remains beneficial across all structural configurations. This result suggests that fragmented systems retain a certain capacity to absorb and utilise technology, potentially supported by policy frameworks, investment subsidies and extension services at the EU level. At the same time, the absence of interaction effects implies that technology does not fundamentally resolve the structural coordination constraints associated with fragmentation, but rather operates within them. The instrumental-variable estimates provide additional nuance. While the direction of the fragmentation effect remains negative, its magnitude becomes less precisely estimated once endogeneity is explicitly addressed. This sensitivity reflects the deep institutional and historical roots of fragmentation, which are only partially captured by available instruments. Importantly, the IV results do not contradict the baseline findings but indicate that the most reliable evidence on fragmentation is provided by the fixed-effects panel models, with IV estimates serving as a complementary robustness check rather than as a definitive causal benchmark.

The robustness analyses further strengthen the empirical conclusions. Across alternative fragmentation indices, different competitiveness measures, multiple climate datasets and alternative standard-error corrections, the negative association between fragmentation and competitiveness remains stable. The effect is particularly pronounced when competitiveness is measured using productivity- and yield-based indicators, whereas income-based measures show greater variability, reflecting the influence of policy transfers and short-term income fluctuations. Together, these results demonstrate that the observed relationship is not an artefact of measurement choices, estimation techniques or data properties. Finally, the inclusion of institutional quality adds an important dimension to the interpretation of results. Governance indicators do not exert a strong direct effect on competitiveness, nor do they significantly interact with fragmentation. This suggests that improvements in institutional quality alone are insufficient to offset structural constraints when fragmentation is high. Instead, institutional factors appear to shape the broader environment in which structural and technological adjustments take place, rather than directly determining performance outcomes.

Overall, the findings indicate that agricultural competitiveness in the European Union is shaped not only by technology, climate or institutions in isolation, but by the internal organisation and coordination of core production-related functions. Functional fragmentation emerges as a persistent structural characteristic that lowers baseline performance and conditions how agricultural systems respond to external drivers. By explicitly linking micro-level functional pressures to macro-level competitiveness outcomes, the analysis provides a system-oriented perspective that complements existing productivity- and technology-focused approaches and clarifies why structurally constrained agricultural systems struggle to fully realise their productive potential.

6. Conclusions

This study provides a system-oriented empirical assessment of agricultural competitiveness in the European Union by examining how the internal organisation of production-related functions shapes performance outcomes across Member States. Using a comprehensive panel dataset covering the period 2004–2023 and integrating structural, technological, institutional and climatic dimensions, the analysis demonstrates that functional fragmentation constitutes a persistent structural constraint on agricultural competitiveness. Countries characterised by higher levels of fragmentation systematically exhibit lower competitive performance, even when controlling for technological intensity, climate conditions and unobserved country-specific factors. The results confirm that technological upgrading remains a key driver of agricultural performance, yet its effectiveness is conditional on the underlying structural configuration of agricultural systems. Technological intensity consistently exerts a positive effect on competitiveness, but it does not fully compensate for the coordination burdens associated with fragmented production structures. Similarly, institutional quality alone does not offset structural disadvantages, suggesting that improvements in governance shape the broader operating environment rather than directly eliminating system-level constraints. Climate anomalies during the observed period are associated with modest average performance gains, reflecting the specific climatic trajectory in Europe over the last two decades, and do not disproportionately penalise more fragmented systems.

By jointly analysing these dimensions within a unified framework, the study contributes to the literature by shifting attention from isolated determinants of performance towards the internal functional architecture of agricultural systems. The findings indicate that agricultural competitiveness cannot be fully understood through inputs, technology or institutions in isolation, but emerges from the alignment and coordination of biological, technological, managerial and institutional functions. Functional fragmentation lowers baseline performance and conditions how agricultural systems respond to external drivers, thereby helping to explain persistent competitiveness gaps across EU Member States. Several limitations should be acknowledged. The analysis is conducted at the national level and therefore cannot capture farm-level heterogeneity or within-country adjustment mechanisms. In addition, the climate effects identified in this study are specific to the 2004–2023 period and may differ under more extreme climatic conditions. Future research could extend the framework to micro-level data, explore dynamic adjustment processes, and examine how functional fragmentation interacts with more severe climate stress or alternative policy regimes.

Overall, the study highlights that improving agricultural competitiveness in structurally constrained systems requires not only continued technological progress but also greater coordination and integration of core production-related functions. Addressing structural fragmentation alongside technological and institutional development appears essential for enhancing the long-term resilience and performance of agricultural systems in the European Union.

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Data Availability Statement: The data used in this study are publicly available from the following sources: FAOSTAT (Food and Agriculture Organization of the United Nations), the Farm Accountancy Data Network (FADN), the World Development Indicators (World Bank), the Worldwide Governance Indicators, and temperature anomaly data from the World Meteorological Organization. No new primary data were generated by the authors.

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Abbreviations

AFF/SIT Theory Agricultural Functional Fragmentation / Structural Incompatibility Theory

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