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Systemic drivers of carbon emissions in farming systems of five EU countries: Pathways for SDG-aligned food security

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ABSTRACT

Agricultural carbon emissions within the European Union present complex systemic challenges requiring integrated approaches that balance environmental objectives with food security imperatives. This study examines systemic drivers of carbon emissions across agricultural value chains in five strategically selected EU countries (France, Hungary, Italy, Poland, and Spain) from 2010 to 2024. Three distinct farming system emission archetypes were identified: (1) intensive processing-dominant systems (Italy generating >8000 kt CO_2 annually, France maintaining 5000–6000 kt CO_2), (2) transitional consumption-driven systems (Poland exhibiting ~7000 kt CO_2 from household consumption, Hungary showing 900 kt CO_2 with transport contributions of 600–900 kt CO_2), and (3) Mediterranean bridge systems (Spain demonstrating 5000–7000 kt CO_2 transport variability). Mediation analysis identified agri-food waste disposal and pesticide manufacturing as strong mediators between emissions and economic outcomes (total effects of 21.0 and 15.0 on GDP respectively), while SDG 12.3 emerged as the strongest mediator explaining 21 % of emissions' impact on GDP. Cross-country scenario testing revealed sustainable food production as the most effective universal policy lever (coefficient 0.266), followed by energy efficiency (0.247) and on-farm energy use (0.237), whereas renewable energy exhibited negative coefficients (−0.085) indicating implementation challenges. Country-specific analyses demonstrated varied responsiveness patterns across 10 % and 20 % intervention scenarios, with France's energy efficiency improvements yielding 0.132–0.264 dietary energy units, while Hungary showed stronger responses to agrifood waste disposal interventions (1.8–3.6 dietary energy units per intervention level). The comprehensive framework demonstrates that coordinated SDG-aligned interventions can simultaneously address carbon emission reduction and food security enhancement, though system-specific implementation strategies remain essential across diverse European agricultural contexts.

1. Introduction

Agricultural activities represent a significant source of greenhouse gas emissions within the European Union, posing critical challenges for climate change mitigation efforts while simultaneously underpinning food production systems that sustain over 440 million people. The EU's commitment to climate neutrality by 2050 and the Farm to Fork Strategy emphasize the need for substantial emission reductions from agricultural sectors without compromising food security for its population (Schneider et al., 2025). However, addressing this dual imperative proves increasingly complex due to the interconnected nature of food systems, which encompass multiple farming subsystems spanning production, processing, distribution, and consumption that contribute variably to overall carbon emissions while simultaneously influencing food availability, access, utilization, and stability across temporal and spatial scales.

Despite growing recognition of the importance of sustainable agricultural transitions, current policy approaches frequently treat components of the food system in isolation, creating analytical blind spots that overlook critical interactions across value chains. Such fragmentation risks generating unintended trade-offs between emission reduction objectives and food security goals aligned with Sustainable Development Goals (SDGs), particularly as these systems exhibit notable heterogeneity across EU member states (Ahmed et al., 2025). This heterogeneity is most pronounced between Mediterranean intensive farming systems with energy-intensive post-harvest processing and transitional economies in Central and Eastern Europe, where consumption-driven activities and evolving infrastructure create distinct carbon footprint

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patterns. The diversity of these farming archetypes demands sophisticated analytical approaches capable of unravelling systemic drivers while identifying context-specific intervention points that can simultaneously address climate and food security imperatives.

Building on this complexity, existing research has predominantly examined agricultural emissions and sustainability from sectoral perspectives, leaving substantial knowledge gaps regarding how emissions propagate through multi-scalar food systems and mediate impacts on food security via SDG implementation pathways. Contemporary studies have largely focused on single-pathway analyses rather than investigating the multiple, simultaneous mediating mechanisms through which carbon emissions influence food security outcomes across interconnected farming subsystems (Rabbi, 2025a). Furthermore, limited attention has been devoted to integrating spatiotemporal, network-based, and hierarchical modelling approaches that can capture the nested structure of farming systems, where farm-level emission drivers are embedded within country-specific policy frameworks including Common Agricultural Policy subsidies and national SDG implementation strategies (Qureshi et al., 2025). The role of intermediary actors such as waste management systems, pesticide manufacturing processes, and policy instruments in mediating these complex relationships has received limited attention, creating important gaps in understanding systemic leverage points for sustainable transitions (Zhu et al., 2023; Fusar and Fontefrancesco, 2024).

These methodological limitations are compounded by temporal dynamics that remain inadequately addressed in existing literature, particularly how farming systems exhibit heterogeneous responses to sustainability interventions across different time horizons (Li et al., 2025). While some changes such as energy efficiency improvements may produce immediate effects, others including soil carbon sequestration require multi-year periods to materialize, creating implementation challenges that current analytical frameworks struggle to capture (Darnhofer et al., 2010). Additionally, critical transition periods such as the 2013 CAP reform implementation and the 2020 Farm to Fork Strategy launch create policy windows that can accelerate or constrain farming system transitions, yet these temporal dynamics are less commonly incorporated into quantitative analyses of emission-food security relationships (Loacker et al., 2025).

This study addresses these substantial research gaps by examining the systemic drivers of carbon emissions across agricultural value chains in five strategically selected EU countries: France, Hungary, Italy, Poland, and Spain. These countries collectively represent approximately 65 % of the EU's agricultural land and 58 % of its total agricultural production, making them highly representative of diverse farming systems across major agro-climatic zones while exemplifying three distinct archetypal systems: intensive processing-dominant systems, transitional consumption-driven systems, and Mediterranean bridge systems (Eurostat, 2025; Mushtaha et al., 2025). Through integration of comprehensive emission inventories, SDG performance indicators, and multidimensional food security metrics, the research employs an innovative multi-method analytical framework combining spatiotemporal contour analysis, correlation network modelling, linear mixed-effects regression, mediation analysis, and policy scenario testing to capture the complex adaptive nature of these systems.

The investigation is guided by three primary research questions that address the identified knowledge gaps: RQ1. How do carbon emissions vary across farming subsystems and archetypal systems within the EU context? RQ2. What are the key mediating pathways through which SDG progress links emissions to food security outcomes across different farming system configurations? RQ3. Which policy intervention levers demonstrate the greatest potential for simultaneously enhancing food security while achieving emission reductions across diverse agricultural contexts?

To address these questions comprehensively, the study pursues four interconnected objectives that advance both theoretical understanding and practical applications. First, it characterizes temporal and spatial patterns of emissions across production, processing, distribution, and consumption subsystems within the selected countries, identifying emission hotspots and evolutionary trajectories that inform targeted intervention strategies. Second, it elucidates the network of systemic interdependencies linking emission sources, SDG performance indicators, and food security dimensions through advanced correlation and network analyses that reveal previously hidden relationships. Third, it quantifies multiple simultaneous mediation pathways through which emissions impact food security domains including dietary energy supply, economic access, water utilization, and political stability, providing valuable insights into the mechanisms driving these relationships. Fourth, it simulates policy scenarios to evaluate the comparative efficacy of interventions including energy efficiency improvements, sustainable food production practices, waste management optimization, and renewable energy adoption across different farming system archetypes.

By adopting a holistic systems approach grounded in socio-ecological systems theory and complex adaptive systems thinking, this research advances fundamental understanding of the causal mechanisms driving emissions and food security relationships within EU agricultural contexts (Geels and Schot, 2007). The findings will provide critical insights for designing coordinated policies that leverage subsystem interactions, address governance fragmentation, and facilitate tailored strategies that account for the heterogeneity of farming system archetypes while maintaining coherent EU-wide sustainability objectives. Through its comprehensive analytical framework and multi-country comparative approach, this investigation addressing important knowledge gap by combining high-resolution empirical data with robust methodological innovations to identify actionable leverage points and optimize policy impact across diverse agricultural contexts.

2. Literature review and theoretical framework

2.1. Systemic carbon emission drivers in EU farming system archetypes

European Union farming systems represent diverse agroecological and socio-economic contexts that generate distinct carbon emission profiles across interconnected subsystems. This diversity presents both challenges and opportunities for systemic interventions targeting sustainable transitions (Kristia et al., 2023). Contemporary EU farming systems can be characterized along multiple dimensions: Mediterranean intensive systems emphasizing high-value horticulture and processing, Central and Eastern European transitional systems balancing productivity with sustainability objectives, and mixed systems incorporating both intensive and extensive practices within integrated crop-livestock frameworks.

The heterogeneity of EU farming systems stems from fundamental differences in agro-climatic conditions, production intensities, market orientations, and policy frameworks. Mediterranean systems, exemplified by regions in France, Italy, and Spain, typically feature energy-intensive post-harvest operations, sophisticated cold-chain logistics, and processing-oriented value chains that generate concentrated emission hotspots. In contrast, farming systems in Central and Eastern Europe, including those in Hungary and Poland, exhibit greater variability in their emission patterns (Ziemblińska et al., 2025). This reflects the ongoing structural transition from a centralized agricultural model toward market oriented, technology enhanced production systems.

Agricultural activities across these diverse farming systems contribute greenhouse gas emissions through multiple pathways, including fossil fuel consumption for machinery and irrigation, livestock operations (particularly methane from enteric fermentation and manure management), and the production of energy-intensive inputs such as synthetic fertilizers and pesticides. The EU's regulatory response has emphasized integrated pest management strategies that minimize reliance on synthetic chemicals while supporting agroecological transitions (Efthimiou, 2025). These policies recognize that emission reduction strategies must be tailored to specific farming system characteristics rather than applying uniform approaches across diverse agricultural contexts (Rabbi, 2024).

Waste management represents a critical leverage point for emission reduction across all farming system types. However, the optimal approaches vary significantly based on system characteristics: intensive systems often require sophisticated anaerobic digestion facilities to process high volumes of organic waste, while extensive systems may benefit more from on-farm composting and integrated nutrient management strategies (Wang et al., 2025). Converting organic waste into valuable soil amendments and reducing methane emissions are two key benefits of composting. This process demonstrates how circular economy principles can be adapted to diverse farming systems. Anaerobic digestion processes that convert organic matter into biogas offer particularly promising pathways for reducing fossil fuel dependence while promoting circular resource use across farming systems (Rahaman et al., 2023; Rabbi and Abdullah, 2024).

2.2. Systemic interactions across farming subsystems: from production to consumption

The carbon footprint of EU farming systems extends far beyond primary agricultural production, encompassing complex interactions among production, processing, distribution, and consumption subsystems. This systems perspective reveals how interventions in one subsystem can generate cascading effects throughout the entire value chain, highlighting the importance of integrated approaches to emission reduction (Ishola, 2025). This shift is largely influenced by increasing regulatory demands and growing consumer expectations for sustainability. Packaging, another major contributor to emissions, calls for urgent innovation, with biodegradable and compostable materials emerging as potential solutions. Reducing excessive packaging use further enhances sustainability efforts.

Post-harvest processing represents a critical subsystem where farming system diversity strongly influences emission patterns. Mediterranean intensive systems typically feature energy-intensive processing operations that transform fresh produce into value-added products, creating concentrated emission sources but also opportunities for renewable energy integration and circular biorefinery development (Castagna et al., 2025). The ongoing transformation toward renewable energy sources in food processing reflects both regulatory pressures and market demands for sustainable production practices (Habib et al., 2025). Packaging systems, while contributing to emissions, serve essential functions in maintaining food quality and reducing post-harvest losses, particularly in supply chains serving distant markets characteristic of intensive farming systems.

Transportation subsystems vary dramatically across farming system types. Mediterranean fruit and vegetable systems require sophisticated cold-chain logistics to maintain product quality over long distribution distances, generating substantial transport-related emissions but also supporting rural economies through market integration. In contrast, locally oriented farming systems may achieve lower transport emissions but face challenges in achieving economies of scale in processing and distribution. The adoption of electric and hydrogen-powered vehicles represents a promising pathway for reducing distribution-related emissions across all farming system types, though implementation challenges vary based on infrastructure availability and economic conditions.

Retail operations and household consumption patterns interact differently with various farming system types. Intensive systems often supply large retail networks that require substantial energy inputs for refrigeration and storage, while also generating opportunities for food waste reduction through supply chain optimization. Consumer-level food waste represents a significant challenge across all systems, with Zhang et al. (2025) and Yang et al. (2025) emphasizing the importance of improved food management practices, proper storage techniques, and meal planning to minimize household waste. The relationship between farming systems and consumer behaviour creates feedback loops that influence production decisions and emission patterns throughout the value chain.

2.3. SDG-mediated pathways in farming system transitions

The Sustainable Development Goals provide a framework for coordinating farming system transitions toward sustainability, with specific targets offering pathways for decoupling agricultural productivity from carbon emissions (Islam, 2025). The implementation of SDGs in farming systems requires recognition that different system types face distinct challenges and opportunities, necessitating differentiated approaches to achieve common sustainability objectives.

SDG 2.4 promotes sustainable food production practices that are inherently context specific. Conservation agriculture and organic farming, identified by Nsabiyeze et al. (2024) as essential strategies for reducing agricultural emissions while enhancing biodiversity and soil health, require different implementation approaches across farming system types. Mediterranean intensive systems may focus on precision agriculture technologies and integrated pest management, while transitional systems in Central and Eastern Europe may prioritize soil health restoration and diversification strategies that build resilience while reducing input dependencies.

Energy system transformations (SDGs 7.2 and 7.3) hold significant potential for farming system decarbonization, though optimal pathways vary significantly across system types. Vezzoni (2025) and Chalkias and Stathatos (2024) demonstrate that renewable energy integration in farming operations can substantially reduce carbon footprints, but the most effective technologies and implementation strategies depend on local resources, energy demands, and economic conditions. Intensive processing-oriented systems may benefit from large-scale renewable energy installations and energy storage systems, while extensive systems may focus on distributed renewable generation and energy efficiency improvements in irrigation and livestock operations.

Infrastructure development (SDG 9.4) serves as a critical enabler for farming system transitions, with Mahmood et al. (2024) emphasizing that appropriate infrastructure investments are fundamental for creating efficient and sustainable food supply chains. However, infrastructure needs vary dramatically across farming system types: intensive systems may require sophisticated biorefinery facilities and advanced logistics networks, while transitional systems may prioritize basic storage facilities and market access improvements that reduce post-harvest losses and support rural development.

Food waste reduction (SDG 12.3) requires system-specific approaches that address the dominant loss and waste patterns in each farming system type. Research by Mustafa et al. (2024) and Han et al. (2021) suggests that success requires tailored strategies: intensive systems may focus on optimizing cold-chain logistics and supply chain coordination, while extensive systems may prioritize on-farm storage improvements and direct marketing channels that reduce losses while capturing value for producers.

Climate policy integration (SDG 13.2) and climate education (SDG 13.3) provide overarching frameworks for coordinating farming system transitions. As Chaiya (2025) and Jia et al. (2025) emphasize that policy tools such as carbon pricing and emissions trading systems must be designed to account for farming system diversity, ensuring that transition pathways are economically viable and socially acceptable across different agricultural contexts. Climate education initiatives must similarly be tailored to the specific knowledge needs and decision-making contexts of different farming system stakeholders.

2.4. Food security outcomes across EU farming system archetypes

Food security outcomes in EU farming systems reflect complex interactions between emission reduction efforts, productivity objectives, and socio-economic conditions that vary significantly across different system types (Rabbi, 2025b). The relationship between carbon emissions and food security is mediated by farming system characteristics, with different archetypes exhibiting distinct vulnerabilities and resilience patterns that influence both environmental and social sustainability outcomes.

Mediterranean intensive farming systems typically achieve high productivity and economic returns while generating concentrated emission sources, creating both challenges and opportunities for sustainable intensification. These systems often provide strong economic foundations for rural communities while serving distant markets, but their reliance on energy-intensive processing and transportation creates vulnerabilities to energy price volatility and climate policy changes. The economic performance of these systems, measured through GDP contributions and employment generation, often supports investments in emission reduction technologies and sustainable practices, creating positive feedback loops between economic and environmental performance.

Central and Eastern European transitional farming systems face distinct food security challenges related to ongoing structural transformations and infrastructure limitations. These systems often exhibit greater variability in both emission patterns and food security outcomes, reflecting heterogeneous adoption of modern technologies and management practices. Political stability plays a particularly important role in these contexts, as consistent policy frameworks are essential for supporting long-term investments in sustainable infrastructure and technology adoption (Wang and Tong, 2025).

The multidimensional nature of food security requires assessment frameworks that capture availability, access, utilization, and stability dimensions across different farming system contexts. Caloric availability may be secure in intensive systems but vulnerable to supply chain disruptions, while extensive systems may provide more stable local food supplies but with limited diversity and market integration. Access dimensions, often measured through economic indicators such as GDP per capita, reflect the capacity of different farming systems to generate income and employment that support food purchasing power for local and regional populations.

Water access and quality (SDG 6) exemplify the complex interactions between farming systems and food security outcomes. Sustainable water management strategies improve access to clean water while supporting agricultural productivity, but the specific approaches must be tailored to local hydrological conditions and farming system characteristics (Sharma et al., 2025). Mediterranean systems may focus on water-efficient irrigation technologies and drought-resistant crops, while transitional systems may prioritize water quality protection and infrastructure development that supports both agricultural and household water security.

The European Union's Farm to Fork Strategy provides a framework for integrating emission reduction and food security objectives across diverse farming systems, emphasizing the need for place-based approaches that respect local conditions while achieving common sustainability goals (Reinhardt, 2023). This strategy promotes measures such as food waste reduction, organic farming support, and local food network strengthening that generate co-benefits for both emission reduction and food security, though the optimal implementation approaches vary significantly across different farming system contexts.

France, Hungary, Italy, Poland, and Spain were selected to represent distinct farming system archetypes. Collectively, these countries encompass the major agricultural contexts within the EU. France and Italy exemplify Mediterranean intensive systems with sophisticated processing and distribution networks, Hungary and Poland reflect Central and Eastern European transitional systems with ongoing modernization processes, while Spain bridges Mediterranean and transitional contexts. This diversity enables analysis of emission-SDG-food security dynamics across the major EU agro-climatic zones and farming system types, providing insights that can inform both national policies and EU-wide strategies for sustainable agricultural development.

2.5. Theoretical framework: systems theory and methodological gaps

The complex interactions among carbon emissions, SDG implementation, and food security outcomes in EU farming systems require a robust theoretical foundation that can accommodate multi-level, multi-temporal dynamics across diverse agricultural contexts. This study draws upon socio-ecological systems (SES) theory and systems thinking to conceptualize farming systems as adaptive, interconnected networks where environmental, economic, and social subsystems co-evolve through feedback mechanisms and threshold effects (Darnhofer et al., 2010).

Socio-ecological systems (SES) theory provides the foundational framework for understanding how farming systems operate as coupled human-natural systems, where carbon emission drivers emerge from the interaction between biophysical processes (e.g., soil carbon dynamics, livestock methane production) and social processes (e.g., policy implementation, farmer decision-making, market dynamics). This theoretical lens enables the analysis of how interventions in one subsystem can influence multiple food security pillars simultaneously. An example of this is how energy efficiency improvements in food processing can propagate through SDG pathways. The SES framework is particularly relevant for understanding path dependence and lock-in effects in farming system transitions, where historical infrastructure investments and institutional arrangements can constrain or enable sustainable transformation pathways (Geels and Schot, 2007).

Systems thinking complements SES theory by providing analytical tools for mapping systemic leverage points where targeted interventions can generate cascading effects across farming system networks. This approach recognizes that farming system transitions involve non-linear dynamics, emergent properties, and multi-scale interactions that cannot be understood through reductionist approaches focusing on individual components in isolation (van Mil et al., 2014).

However, existing methodological approaches in farming system research exhibit several critical limitations that constrain understanding of emissions-SDG-food security dynamics. First, most studies employ static, cross-sectional analyses that unable to capture the temporal dynamics of farming system transitions, particularly how transition pathways evolve differently across farming system archetypes in response to policy interventions and external shocks (Darnhofer et al., 2010). Second, conventional econometric approaches often treat farming systems as homogeneous units, neglecting the hierarchical structure where farm-level decisions are embedded within country-specific policy frameworks (e.g., CAP subsidy structures) that create systematic variation in emission patterns and SDG implementation effectiveness (Quiroga et al., 2017).

Third, existing mediation analyses in agricultural sustainability research typically focus on single pathways rather than multiple, simultaneous mediating mechanisms through which carbon emissions influence food security outcomes. This limitation is particularly problematic for understanding SDG interactions, where progress on one target (e.g., SDG 12.3 food waste reduction) may simultaneously influence multiple food security dimensions through different causal pathways (Farrukh et al., 2020; Barbosa and Cansino, 2024). Fourth, scenario analysis approaches in farming system research often rely on linear sensitivity testing rather than systems-based scenario modelling that can capture threshold effects and non-linear responses characteristic of complex adaptive systems (Le et al., 2010).

The temporal dimension of farming system transitions presents additional methodological challenges that remain inadequately addressed in existing literature. Farming systems exhibit temporal heterogeneity in their response to sustainability interventions, with some changes (e.g., energy efficiency improvements) producing immediate effects while others (e.g., soil carbon sequestration) require multi-year time horizons to materialize. Furthermore, critical transition periods, such as the implementation of the 2013 CAP reform or the launch of the 2020 Farm to Fork Strategy, create policy windows that can accelerate or constrain farming system transitions (Frank and Schanz, 2025). A key analytical gap is that these temporal dynamics are rarely incorporated into quantitative analyses of the emissions-food security relationship.

Policy coherence challenges represent another under-explored dimension in existing research. The implementation of SDG targets in farming systems occurs within complex multi-level governance structures where EU-level policies (e.g., climate targets), national policies (e.g., agricultural subsidies), and local policies (e.g., land use regulations) interact to create heterogeneous policy landscapes across member states. This policy fragmentation can generate implementation gaps where ambitious SDG targets are undermined by conflicting policy incentives at different governance levels, but systematic analysis of these coherence challenges remains limited in existing literature.

These theoretical and methodological gaps necessitate integrated analytical approaches that can simultaneously capture: (1) multi-level interactions between farm-level emission drivers and country-level policy contexts; (2) temporal dynamics of farming system transitions across different time horizons; (3) multiple mediation pathways linking emissions to food security through SDG implementation; and (4) systems-level scenario responses that account for non-linear threshold effects and cascading impacts across subsystems. To address these limitations, a methodological framework was designed to provide robust empirical foundations for understanding systemic drivers of sustainable transitions in EU farming systems. This framework integrates spatio-temporal analysis, network analysis, linear mixed effects modelling, mediation analysis, and scenario modelling.

3. Methods and methodology

Addressing the methodological limitations identified in existing farming system research, this study employs an integrated quantitative framework designed to capture the systemic interactions between carbon emission drivers, SDG implementation pathways, and food security outcomes across interconnected farming subsystems. The methodological approach is grounded in socio-ecological systems theory and systems thinking (as outlined in Section 2.5), enabling analysis of multi-level interactions, temporal dynamics, and multiple mediation pathways that characterize farming system transitions. The analytical framework addresses three critical methodological gaps: (1) cross-subsystem interactions within EU farming systems, (2) temporal heterogeneity in farming system responses to sustainability interventions, and (3) multiple simultaneous mediating mechanisms through which carbon emissions influence food security via SDG progress.

The integrated analytical framework employs five complementary techniques specifically selected to address the methodological limitations identified in farming system transition research. Each technique targets specific aspects of the systemic interactions between emission drivers, SDG pathways, and food security outcomes:

(1) Spatiotemporal contour analysis maps emission hotspots and temporal shifts across farming subsystems, addressing the need for systems-level visualization of emission patterns; (2) Correlation network analysis quantifies systemic interdependencies between emission drivers, SDG targets, and food security indicators; (3) Linear mixed-effects modelling (LME) captures hierarchical interactions inherent to farming systems, where country-level random effects (e.g., CAP subsidy structures, national policy frameworks) influence farm-level emission drivers; (4) Mediation analysis specifically examines multiple simultaneous pathways through which SDG progress mediates relationships between emission hotspots and food security outcomes across subsystems; and (5) Scenario analysis projects systems-level responses to policy interventions, accounting for non-linear threshold effects and cascading impacts across farming system networks.

3.1. Data source and collection

Data were derived from two primary sources: the Food and Agriculture Organization of the United Nations (FAO) database (FAO, 2025a, b) and European statistics database (EU, 2025) to ensure a strong analytical foundation. These sources were selected for their credibility, providing the reliability and accuracy necessary for rigorous, comprehensive analysis. The dataset encompasses a wide span of variables essential for this study, containing data on carbon emissions throughout the food supply chain from primary production to end-usage. This comprehensive "farm-to-fork" perspective includes emissions from on-farm energy use, waste disposal in agrifood systems, pesticide production, food processing, packaging, transportation, retail, and household consumption. Such granular coverage enables identification of both emission hotspots and potential intervention leverage points across the entire agricultural value chain.

The analysis encompasses both carbon emissions data and SDG indicators closely tied to sustainable food systems. Specifically, the study examines SDG targets related to sustainable food production, clean energy promotion, infrastructure development, food waste prevention, climate policy implementation, and climate education. These SDG dimensions enable assessment of compatibility between carbon reduction efforts and broader sustainability objectives across the farming system categories outlined in the Category-Pillar framework.

3.1.1. Data quality and missing values

This study analyzed carbon emissions, Sustainable Development Goals (SDGs), and food security data from 2010 to 2024, employing imputation techniques to address missing values for 2023 and 2024. To handle missing data, the researcher adopted the k-nearest neighbors (KNN) imputation approach, implemented using Python's scikit-learn library. The KNN algorithm is a versatile and widely used machine learning algorithm primarily employed for both classification and regression tasks that operates on the principle that data points with similar feature values are likely to have similar output values (Troyanskaya et al., 2001). Unlike many other machine learning algorithms, KNN is considered a non-parametric and lazy learning algorithm. The KNN imputation approach has been extensively validated in environmental and agricultural research contexts, demonstrating superior performance compared to traditional mean-based methods (Junninen et al., 2004; Beretta and Santaniello, 2016). After evaluating different configurations through cross-validation, selecting $k = 5$ proved to be the most effective for this dataset.

The KNN method estimates missing values by identifying data points with similar patterns and using their values to fill the gaps. For numerical variables such as "Pesticides Manufacturing" and "Climate Policy," the imputation follows the formula:

$$\hat{y}_i = \frac{1}{k}\sum_{j=1}^{k} y_{\mathcal{N}_i(j)} \tag{1}$$

where $\widetilde{y_i}$ represents the estimated missing value, $\mathcal{N}_i(j)$ denotes the index of the j th nearest neighbor to data point i, and $y_{\mathcal{N}_i(j)}$ corresponds to its observed value.

For categorical variables such as "Food packaging" classification, the imputed value is determined by the most frequently occurring category among the nearest neighbors:

$$\hat{y}_i = \arg\max_{c} \sum_{j=1}^{k} \mathbf{1}\left(y_{\mathcal{N}_i(j)} = c\right) \tag{2}$$

where $1(\cdot)$ is an indicator function that counts occurrences of category ccc among the k neighbors.

To measure similarity between data points, the distance function is defined as:

$$D(x_i, x_j) = \left(\sum_{m=1}^{M} |x_{i,m} - x_{j,m}|^p \right)^{\frac{1}{p}} \tag{3}$$

where x_{il} and x_{jl} are feature values of observations x_i and x_j, with m representing the number of features. When $p = 2$, this simplifies to the standard Euclidean distance:

$$D(x_i, x_j) = \sqrt{\sum_{m=1}^{M} (x_{i,m} - x_{j,m})^2} \tag{4}$$

This imputation strategy preserved regional variations in sustainability indicators while preventing distortions that could arise from simpler mean-based imputation techniques. The methodological approach aligns with established best practices in environmental data analysis and has been demonstrated to maintain the underlying structure and temporal patterns essential for robust agricultural sustainability research (Junninen et al., 2004; Beretta and Santaniello, 2016).

3.1.2. *Hierarchical data structure and farming system typologies*

The dataset exhibits a hierarchical structure reflecting the embedded nature of farming system transitions, where farm-level emission drivers are nested within country-specific policy frameworks (e.g., CAP subsidy structures, national SDG implementation strategies). This hierarchical organization necessitates analytical approaches capable of decomposing variance at multiple scales while accounting for systematic differences across farming system archetypes.

The five selected countries represent distinct farming system typologies that enable comparative analysis across major EU agro-climatic zones: France and Italy exemplify intensive Mediterranean systems characterized by high-value crop production and energy-intensive processing; Poland and Hungary represent Central/Eastern European transitional economies with legacy infrastructure and evolving policy frameworks; while Spain bridges both contexts with diverse regional farming systems. This strategic sampling design enables identification of systemic leverage points that transcend individual country contexts while capturing heterogeneity in emission-SDG-food security dynamics across different farming system archetypes.

The temporal scope (2010–2024) captures critical transition periods including the 2013 CAP reform implementation and the 2020 Farm to Fork Strategy launch, enabling analysis of policy window effects and transition pathway dynamics within the broader context of EU sustainable development policy evolution.

3.2. *Variable selection and conceptual framework*

A comprehensive understanding of the relationship between carbon emissions, the Sustainable Development Goals (SDGs), and food security necessitates systematic variable selection. These indicators are essential for accurately modelling carbon emissions' impact on SDG advancement. Table 1 presents a concise summary of the key indicators chosen to encapsulate this multifaceted relationship.

To systematically organise the complex interactions within farming systems, variables were classified into three primary Categories with corresponding theoretical Pillars as detailed in Table 1. CO_2 Emissions Sources encompass five pillars spanning the entire value chain: Farm Production (on-farm energy use, pesticide manufacturing), Post-Harvest Processing (food processing, packaging), Distribution Systems (food transport, retail), Consumption Patterns (household food consumption), and Waste Management (agri-food systems waste disposal). Policy Levers represent seven SDG-aligned pillars: Sustainable Production (SDG-2.4), Renewable Energy (SDG-7.2), Energy Efficiency (SDG-7.3), Infrastructure Development (SDG-9.4), Waste Reduction (SDG-12.3), Climate Policy (SDGs-13.2), and Climate Education (SDG-13.3). Food Security Dimensions correspond to the four established pillars: Food Availability, Food Access, Food Utilization, and Food Stability.

To visualize the systemic relationships among the variables presented in Table 1, Fig. 1 provides a conceptual framework that maps the interconnected pathways through which carbon emission drivers influence food security outcomes via SDG implementation. This framework guides the analytical approach by illustrating how emissions from farming subsystems (production, processing, distribution, consumption) mediate food security through policy levers represented by the selected SDG targets.

Fig. 1 presents the conceptual framework underpinning this study. This conceptual framework illustrates the systemic relationships among carbon emission drivers across farming subsystems (production, processing, distribution, consumption), SDG implementation pathways (policy levers), and food security outcomes in France, Hungary, Italy, Poland, and Spain. Arrows indicate both direct and mediated effects where emission drivers influence food security directly and indirectly through SDG progress. The framework reflects the mediation and scenario analyses employed in this study, demonstrating how interventions in one subsystem (e.g., energy efficiency) can propagate through SDG pathways to affect multiple food security pillars, supporting a systems-based approach to policy design in EU farming systems.

3.2.1. *Software and analytical tools*

Statistical analyses, including spatiotemporal contour analysis, linear mixed-effects modelling (LME), and robustness checks, were performed using MATLAB 2024b (MathWorks), leveraging its superior matrix computation capabilities and built-in statistical toolboxes for hierarchical data modelling. Python version 3.13.1, implemented primarily through Visual Studio Code, facilitated correlation network analysis, mediation modelling, and scenario simulation due to its extensive analytical ecosystem.

Key Python libraries included scikit-learn (v1.3.0) for k-nearest neighbor (KNN) imputation and cross-validation procedures, statsmodels (v0.14.0) for ordinary least squares regression and mediation analysis, NetworkX (v3.1) for correlation network construction, and NumPy/Pandas for data manipulation. Data visualization utilized both platforms: MATLAB's native plotting functions for spatiotemporal contour maps and Python's Matplotlib (v3.7.1) and Seaborn (v0.12.2) libraries for network visualizations and scenario outputs.

This dual-platform approach optimized computational efficiency while ensuring analytical rigor. MATLAB excelled in complex statistical modelling and numerical optimization, while Python provided flexibility for network analysis and advanced statistical procedures. Visual Studio Code enhanced Python development through integrated debugging, version control, and comprehensive code management.

Computational workflows were documented through detailed scripts with parameter specifications and reproducibility guidelines. All analytical procedures included comprehensive validation checks, diagnostic testing, and sensitivity analyses to ensure methodological robustness. The combination of MATLAB's specialized statistical capabilities and Python's versatile ecosystem, managed through Visual Studio Code's development environment, enabled efficient analysis of complex, multi-dimensional panel datasets while maintaining full reproducibility and transparency for peer verification.

3.3. *Analytical procedure*

3.3.1. *Spatiotemporal contour analysis*

The spatiotemporal dynamics of carbon emissions were analyzed using Equations (5)–(7) to map emission trends across countries and subsystems (Fig. 2). This approach identified emission hotspots and temporal shifts in France, Hungary, Italy, Poland, and Spain.

The first step involves filtering the emissions data for each country and transforming it into a format suitable for analysis. For every country, emissions from each source are extracted and organized by year, allowing for a detailed examination of annual variations.

Table 1
Key variables linking carbon emissions, SDGs, and food security in EU farming systems.

Category	Pillar	Variables	Data Source	Measurement	Cross-Domain Impact	Farming systems role
CO_2 Emissions Sources	Farm Production	On-farm energy use	FAO	Kilotons of CO_2	Links farm-level energy decisions to SDG 7.3 (energy efficiency) and food availability via irrigation system efficiency.	Quantifies energy intensity in EU crop-livestock systems and renewable integration potential.
		Pesticides Manufacturing	FAO	Kilotons of CO_2	Affects SDG 2.4 (sustainable agriculture) through soil health degradation and biodiversity loss.	Reflects chemical input dependency in conventional EU farming vs. agroecological alternatives.
	Post-Harvest Processing	Food Processing	FAO	Kilotons of CO_2	Impacts SDG 12.3 (food waste) via processing losses and SDG 9.4 through infrastructure efficiency.	Highlights energy-intensity of EU post-harvest subsystems and circular biorefinery potential.
		Food Packaging	FAO	Kilotons of CO_2	Packaging emissions contribute to environmental degradation, intersecting with SDG 12.3 (waste) and SDG 13.2 (climate policy), and can influence food safety and loss rates.	Links to distribution subsystem sustainability and material circularity
	Distribution Systems	Food Transport	FAO	Kilotons of CO_2	Influences SDG 13.2 (climate policy) compliance and rural food access in peripheral EU regions.	Measures cold-chain logistics efficiency in Mediterranean fruit/vegetable supply chains.
		Food Retail	FAO	Kilotons of CO_2	Influences SDG 13.2 (climate policy) compliance and rural food access in peripheral EU regions.	Reflects energy use in final distribution networks
	Consumption Patterns	Food Household Consumption	FAO	Kilotons of CO_2	Consumer-level emissions are shaped by upstream production and processing, with implications for food utilization, waste generation, and the realization of multiple SDGs.	Ties consumer behavior to farm-level production decisions
	Waste Management	Agrifood Systems Waste Disposal	FAO	Kilotons of CO_2	Waste disposal emissions affect environmental health, resource efficiency (SDG 12.3), and long-term food security by influencing the sustainability of the entire value chain.	Quantifies closed-loop resource recovery potential in farming systems
Policy Levers	Sustainable Production (SDG-2.4)	Sustainable food production	Eurostat	Index (0–100)	Mediates emissions-food security tradeoffs through agroecological practice adoption rates.	Tracks CAP-aligned transitions to integrated crop-livestock systems in EU member states.
	Renewable Energy (SDG-7.2)	Renewable Energy	Eurostat	Percentage (%)	Transition to solar/wind energy in food processing reduces fossil fuel reliance, lowering emissions and stabilizing energy costs for farmers.	Enables decentralized renewable energy systems for irrigation and processing, reducing GHG hotspots in farm operations.
	Energy Efficiency (SDG-7.3)	Energy Efficiency	Eurostat	Index (0–100)	Reduces on-farm emissions while affecting production costs and food affordability.	Evaluates precision agriculture adoption in EU cereal/poultry systems.
	Infrastructure Development (SDG-9.4)	Sustainable Infrastructure	Eurostat	Index (0–100)	Resilient infrastructure reduces post-harvest losses and transport emissions, enhancing food access in rural/urban markets.	Supports circular economy models (e.g., biogas plants) by linking farm waste to energy generation and nutrient recycling.
	Waste Reduction (SDG-12.3)	Food Waste	Eurostat	Kilograms per capita (kg/capita)	Halving retail/consumer waste redirects resources to food-insecure populations while reducing landfill methane emissions.	Drives farm-to-retail collaborations to optimize supply chains, minimizing systemic inefficiencies in perishable goods.
	Climate Policy (SDG-13.2)	Climate Policy	Eurostat	Index (0–100)	Carbon pricing incentivizes emission reductions in agro-industries, fostering innovation in low-carbon farming practices.	Aligns CAP subsidies with climate-smart agriculture, accelerating adoption of drip irrigation and no-till farming.
	Climate Education (SDG-13.3)	Climate Education	Eurostat	Index (0–100)	Training farmers in emission monitoring and adaptation strategies builds capacity for resilient, sustainable food systems.	Strengthens knowledge-sharing networks to mainstream agroecology and reduce pesticide overuse.
Food Security Dimensions	Food Availability	Average Dietary Energy Supply	FAO	Percentage (%)	Reflects synergies between emission-efficient farming and yield stability, ensuring calorie availability amid climate shocks.	Tracks how regenerative practices (e.g., cover cropping) maintain productivity while sequestering carbon.
	Food Access	Gross Domestic Product	FAO	USD	Economic growth from sustainable agri-industries funds rural infrastructure, improving market access for smallholders.	Measures ROI of SDG-aligned investments (e.g., solar-powered irrigation) in enhancing farm incomes and regional equity.
	Food Utilization	Percentage of Population Using Safe Drinking Water	FAO	Percentage (%)	Sustainable water management in agriculture reduces pollution from fertilizers/pesticides, safeguarding water quality for communities.	Links water-efficient practices (e.g., drip irrigation) to reduced aquifer depletion and safer household water access.
	Food Stability	Political Stability	FAO	Index (2.5–2.5)	Stable governance ensures continuity of SDG-focused policies, mitigating conflicts over resource scarcity exacerbated by emissions.	Correlates policy coherence (e.g., CAP reforms) with farmer adoption of climate-resilient practices, securing long-term output.

Notes:
- kt CO_2 = kilotons carbon dioxide.
- CAP = Common Agricultural Policy.
- SDG = Sustainable Development Goal.
- All indices scaled 0–100 unless otherwise specified.

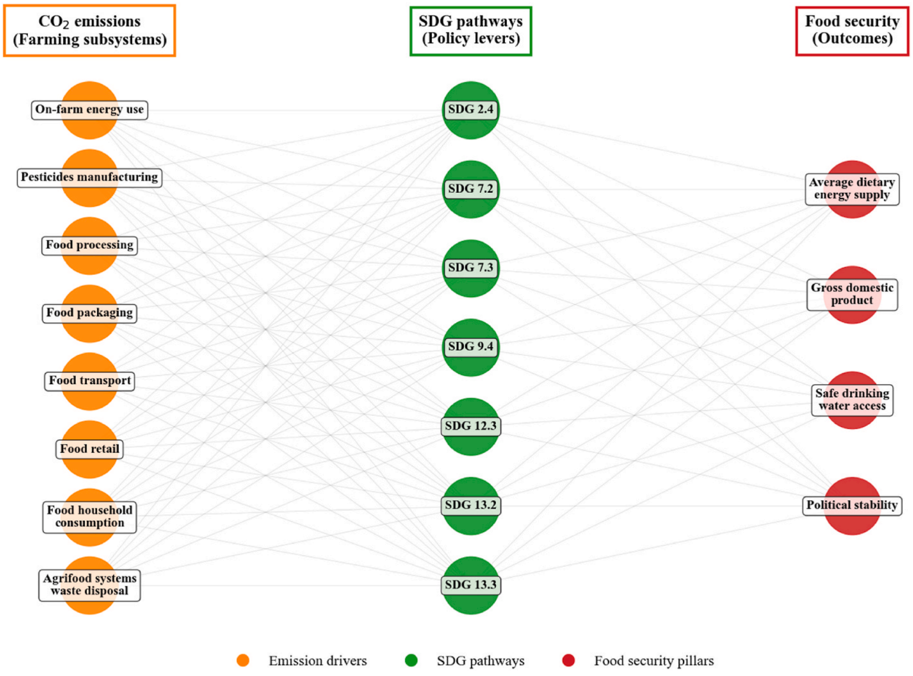


Fig. 1. Conceptual framework linking carbon emission drivers, SDG pathways, and food security outcomes.

$$\mathbf{Emissions}_{country}(t) = \begin{bmatrix} E_{farm}(t) \\ E_{pesticides}(t) \\ E_{processing}(t) \\ E_{packaging}(t) \\ E_{transport}(t) \\ E_{retail}(t) \\ E_{household}(t) \\ E_{waste}(t) \end{bmatrix} \tag{5}$$

where $\text{Emissions}_{\text{country}}(t)$ represents emissions from each specific source in year t.

A crucial aspect of the analysis is examining the changes in emissions over time for each variable. By calculating the year-over-year differences, the study identifies trends and patterns that provide insight into how emissions from each source evolve. The year-over-year change in emissions for each variable is computed using following equation:

$$\Delta E_{variable}(t) = E_{variable}(t+1) - E_{variable}(t) \tag{6}$$

Here the year-over-year change $\Delta E_{\text{variable}}(t)$ highlights significant trends in emissions from different sectors, aiding in identifying key drivers of carbon emissions.

Finally, a comparative analysis across the countries is conducted to evaluate the contribution of each emissions source to the overall carbon footprint. By aggregating the emissions data over the entire period and calculating the proportion each source contributes to the total emissions, the study identifies key areas for targeted interventions. To compare the emissions trends across countries using the following metric:

$$\text{ComparisonMetric}_{variable} = \frac{\sum_{t=2010}^{2024} E_{variable}^{country}(t)}{\text{TotalEmissions}_{country}} \tag{7}$$

This metric evaluates the contribution of each variable to the total emissions for each country over the study period. Here $E_{\text{variable}}^{\text{country}}$ represents the emissions from a specific variable (e.g., on-farm energy use, food processing) in each country at time t. And Total $\text{Emissions}^{\text{country}}$ is the sum of emissions from all variables in that country over the analysis period (2010–2024). The combination of spatiotemporal analysis and comparative insights ensures a well-rounded perspective that can inform both national and EU-level environmental policies.

3.3.2. *Correlation network analysis*

Researcher employed the Pearson correlation coefficient in Fig. 3 to explore the interrelationships between pairs of variables, as calculated using Equation (8). This analysis was conducted for each distinct pair of variables drawn from different sets. For instance, the correlation between Carbon Emissions and Sustainable Development Goals (SDGs), Carbon Emissions and Food Security, and SDGs and Food Security were examined. For each pair of variables X and Y from different sets (e.g., Carbon Emissions vs. SDGs, Carbon Emissions vs. Food Security, SDGs vs. Food Security), the Pearson correlation coefficient r is calculated as:

$$r_{XY} = \frac{\sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \overline{X})^2} \sqrt{\sum_{i=1}^{n} (Y_i - \overline{Y})^2}} \tag{8}$$

3.3.3. *Linear mixed-effects modelling (LME)*

The LME framework specifically addresses the hierarchical structure of farming system data by decomposing variance into fixed effects

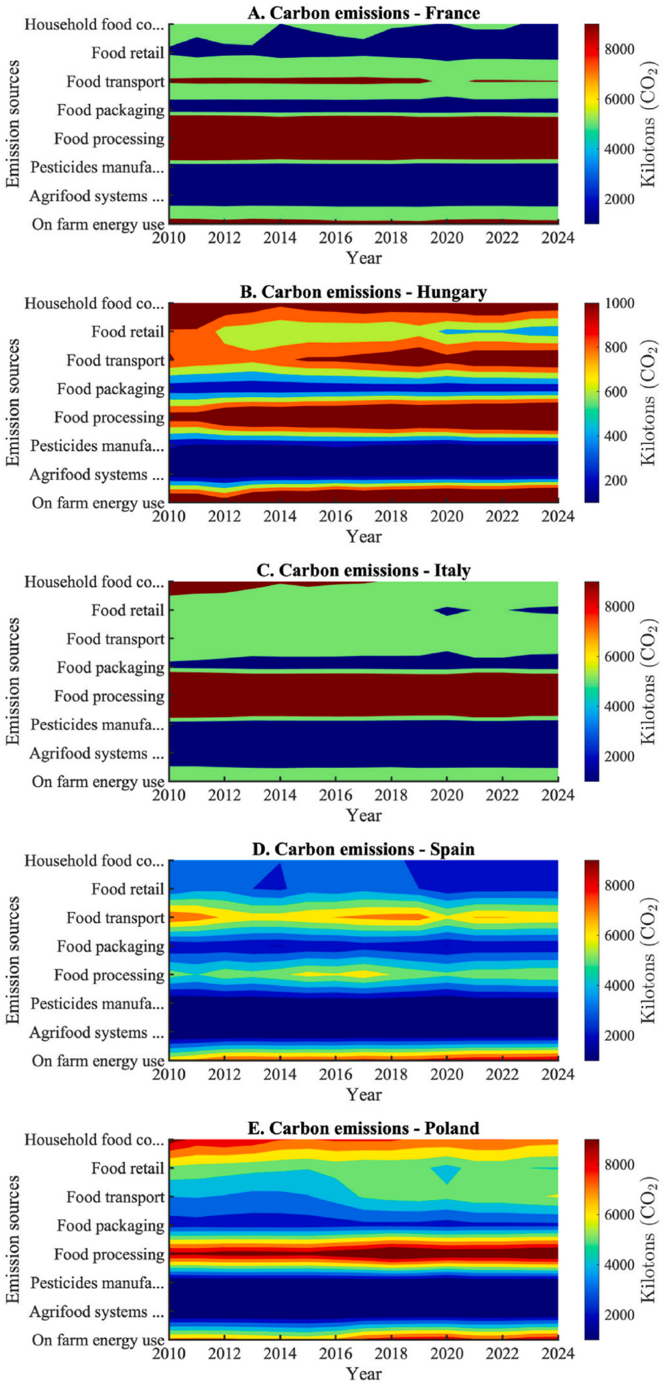


Fig. 2. Spatiotemporal patterns of subsystem-level carbon emissions across EU farming systems (2010–2024).

(representing systematic relationships across all countries) and random effects (capturing country-specific deviations due to policy frameworks, institutional arrangements, and agroecological conditions). This approach enables identification of systemic patterns while accounting for heterogeneity across farming system typologies.

LME models assessed fixed and random effects using Equations (9) and (10), as presented in Tables 2–5. For computing the Linear Mixed-Effects Model first step involves loading data from three datasets $D1$ for Carbon Emissions, $D2$ for SDGs, and $D3$ for Food Security. And the merged dataset D_{merged} is created using a join operation on the Country and Year. This can be represented as:

$$D_{merged} = D_1 \bowtie D_2 \bowtie D_3 \tag{9}$$

where $\bowtie$ denotes the join operation.

The random effects structure captures unobserved country-level heterogeneity including CAP subsidy allocation patterns, national SDG implementation strategies, institutional capacity for policy coordination, and agroecological constraints that systematically influence emission-food security relationships. By explicitly modelling these sources of heterogeneity, the LME framework prevents spurious correlations that might arise from aggregating across diverse farming system contexts.

The equation used in the LME model is:

$$Y_{ij} = \beta_0 + \sum_{k=1}^{p} \beta_k X_{ijk} + u_j + \epsilon_{ij} \tag{10}$$

In this model, food security, denoted as Y_{ij} for the i-th observation in the j-th country, is the dependent variable. The model includes a fixed intercept (β_0) and fixed coefficients (β_k) for each independent variable X_{ijk}. Additionally, the model incorporates a random effect, u_j specific to each country (j), and a residual error term present as ϵ_{ij}. The random effect accounts for unobserved country-level heterogeneity that may influence food security outcomes.

3.3.4. *Mediation analysis*

Mediation analysis addresses the critical research gap regarding multiple simultaneous mediating mechanisms through which carbon emissions influence food security outcomes. Unlike conventional approaches that examine single pathways, this analysis quantifies how multiple SDG targets simultaneously mediate emissions' impacts, enabling identification of policy leverage points within complex farming system networks. The mediation framework specifically tests theoretical propositions from socio-ecological systems theory regarding indirect effects and feedback mechanisms that characterize sustainable transitions in coupled human-natural systems.

Two Ordinary Least Squares (OLS) regression models underpinned this analysis. The first, the mediator model, assessed the influence of the independent variable on the mediator. This model provides crucial insights into how the independent variable impacts the potential intermediary factor.

$$\text{Mediator} = \beta_0 + \beta_{IV}\ \text{IV} + \epsilon \tag{11}$$

The second model, the dependent variable model, evaluated the combined influence of the independent variable and the mediator on the dependent variable.

$$\text{DV} = \beta_0 + \beta_{IV}\ \text{IV} + \beta_M\ \text{Mediator} + \epsilon \tag{12}$$

This model allows for a comprehensive understanding of the overall impact, considering both the direct and indirect pathways. The indirect effect $\beta_1 + \beta_2$ was calculated by multiplying the coefficient of the independent variable (IV) from the mediator model with the coefficient of the mediator from the dependent variable (DV) model (β_2). The direct effect (β_1) was derived directly from the dependent variable model. Finally, the total effect was determined by summing the direct and indirect effects. This approach provides a nuanced understanding of the complex interplay between carbon emissions, SDGs, and food security outcomes.

3.3.5. *Scenario analysis*

Policy scenarios (Equations (13)–(15)) simulated 10 % and 20 % changes in key variables to project impacts on food security (Figs. 6–10), informing country-specific interventions. The relationship between these variables is described by the following equation:

$$y_{i,j} = \beta_0 + \beta_1\ IV_{i,j} + \epsilon_{i,j} \tag{13}$$

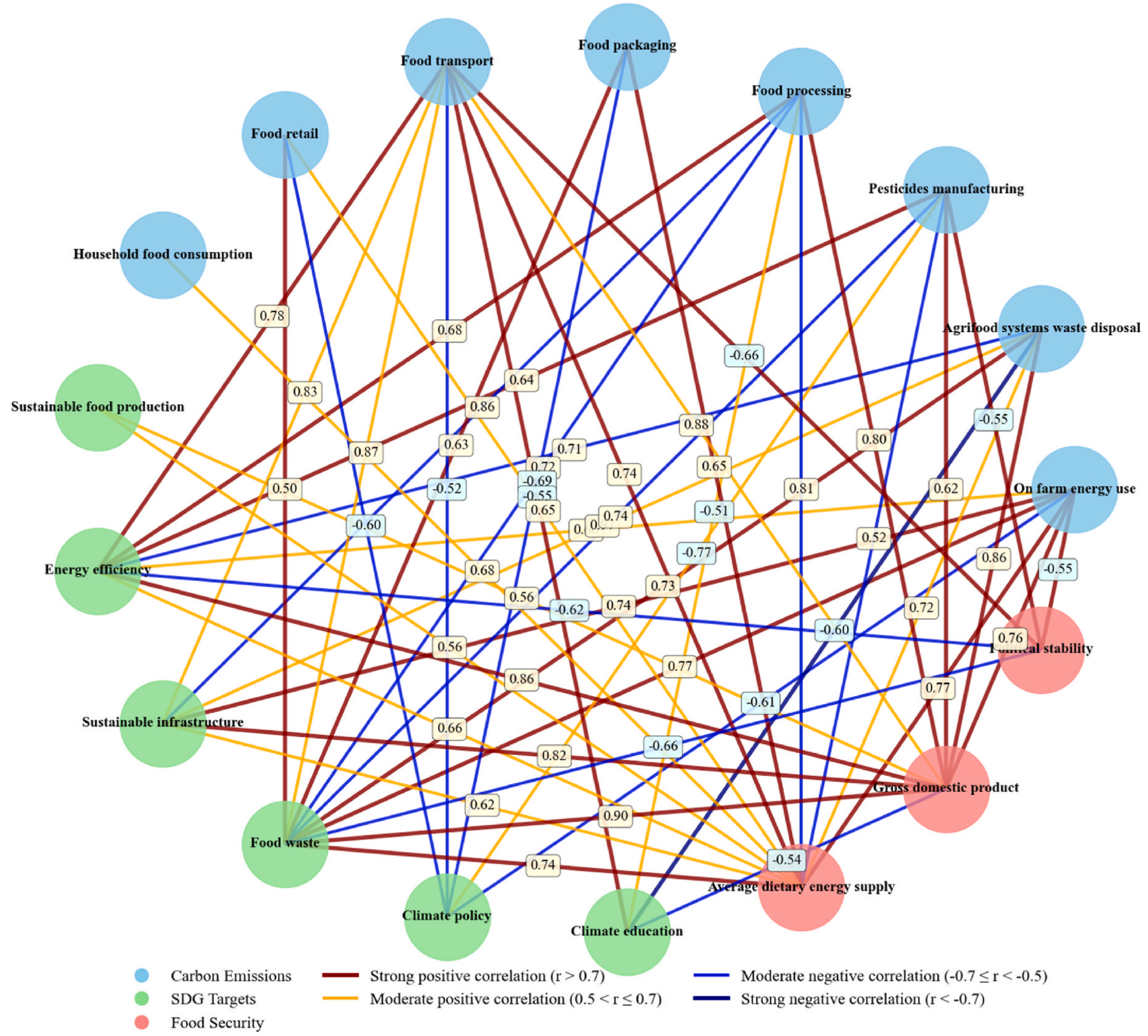


Fig. 3. Interdependence network analysis of carbon emissions, SDG progress, and food security metrics in EU farming systems.

Here, $y_{i,j}$ denotes the dependent variable (DV) for country i in year j, representing the food security indicator under consideration. The term β_0 is the intercept, capturing the baseline level of the dependent variable when the independent variable (IV) is zero. The coefficient β_1 measures the extent to which a one-unit change in the independent variable $IV_{i,j}$ influences the dependent variable. The residual term $\epsilon_{i,j}$ accounts for other factors not included in the model that may affect the dependent variable.

For scenario analysis, researcher introduced a percentage change in the independent variable to simulate its potential variations. This adjustment is defined as:

$$IV^{*}_{i,j} = IV_{i,j}\,(1 + \Delta) \tag{14}$$

where Δ represents the percentage change applied, including four scenarios: 10 % increase ($\Delta = +0.10$), 10 % decrease ($\Delta = -0.10$), 20 % increase ($\Delta = +0.20$), and 20 % decrease ($\Delta = -0.20$). The resulting change in the dependent variable due to the change in the independent variable is estimated by:

$$\Delta y_{i,j} = \beta_1\,\Delta\,IV_{i,j} \tag{15}$$

This calculation allows quantification of food security sensitivity across moderate (±10 %) and substantial (±20 %) fluctuations in key environmental and sustainability-related factors, providing policymakers with both incremental and transformative intervention scenarios.

The scenario analysis framework addresses limitations in existing farming system research by modelling systems-level responses that account for threshold effects and non-linear dynamics characteristic of complex adaptive systems. Rather than assuming linear sensitivity, the approach captures emergent properties and cascading effects that arise when interventions in one subsystem propagate through SDG pathways to influence multiple food security dimensions simultaneously. The inclusion of both 10 % and 20 % change scenarios enables identification of potential tipping points and non-linear responses, where moderate changes may produce proportional effects while substantial changes reveal threshold behaviours and systemic leverage points for targeted interventions across interconnected farming system networks.

4. Results and analysis

Results are organized according to the Category-Pillar framework established in Table 1, examining how emissions across value chain pillars (Farm Production through Waste Management) interact with policy lever pillars (SDG-aligned interventions) to influence food security dimension pillars across the five EU countries. The analytical framework employed five complementary techniques to examine systemic relationships between carbon emissions, SDG progress, and food

Table 2

Mixed-effects analysis of food availability determinants in EU farming systems.

Variables	Coefficient	SE	p-Value	Lower	Upper
On farm energy use	0.0022	0.0007	**0.0031**	0.0008	0.0036
Agrifood systems waste disposal	−0.0117	0.0331	0.7258	−0.0779	0.0545
Pesticides manufacturing	−0.0057	0.0026	**0.0351**	−0.0110	−0.0004
Food processing	0.0003	0.0002	0.2491	−0.0002	0.0007
Food packaging	0.0025	0.0027	0.3591	−0.0029	0.0078
Food transport	0.0006	0.0010	0.5178	−0.0013	0.0026
Food retail	−0.0033	0.0014	**0.0196**	−0.0060	−0.0005
Household food consumption	0.0028	0.0007	**0.0003**	0.0013	0.0042
Sustainable food production	1.0969	0.3106	**0.0008**	0.4755	1.7183
Renewable energy	−0.0129	0.0110	0.2479	−0.0350	0.0092
Energy efficiency	0.5222	1.2823	0.6853	−2.0437	3.0881
Sustainable infrastructure	−0.0020	0.0016	0.1993	−0.0051	0.0011
Food waste	6.8476	3.2741	**0.0408**	0.2962	13.3990
Climate policy	−0.0000	0.0000	0.8529	−0.0001	0.0001
Climate education	0.0196	0.0288	0.4986	−0.0380	0.0771

Note:

- All models estimated using Linear Mixed-Effects Regression with REML method.
- Random intercepts by Country account for unobserved country-level heterogeneity.
- Sample includes 75 observations across 5 EU countries (France, Hungary, Italy, Poland, Spain) from 2010 to 2024.
- Significance levels: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$ (highlighted in bold).
- Confidence intervals represent 95 % credible intervals for coefficient estimates.
- SE denotes standard error of coefficient estimates.
- Variables tested for multicollinearity using Variance Inflation Factor (VIF).
- Model assumes compound symmetry covariance structure for temporal correlation.
- Missing data handled through listwise deletion of incomplete observations.

security outcomes. equations 1–15 outlined in the Methods section serve as the foundation for all analytical procedures presented below. Results are presented sequentially, building from descriptive patterns (4.1) through network relationships (4.2), statistical modelling (4.3), mediation pathways (4.4), to policy scenario projections (4.5), culminating in cross-country synthesis (4.6), creating an integrated understanding of farming system dynamics.

4.1. Spatiotemporal carbon emission patterns across EU farming systems

Fig. 2 illustrates the spatiotemporal dynamics of carbon emissions across five EU countries, calculated using Equations (5)–(7). These equations aggregate emissions by source and compute year-over-year changes and proportional contributions for each country.

France exhibits relatively stable emission patterns, with food processing emerging as a dominant contributor, consistently generating around 5000–6000 kilotons of carbon emissions annually. However, carbon emission profile reveals decoupling between production and processing subsystems, where energy-intensive food processing (8000 kt CO_2) offsets gains from sustainable on-farm practices. This systemic inefficiency highlights the need for integrated biorefinery models linking agricultural waste to renewable energy generation. The household food consumption sector in France shows moderate fluctuations from 6000 to 7000 annually, with a slight upward trend from 2018 onwards. Notably, the food transport sector maintains a consistent emission level throughout the period, appearing as a distinct band in the middle range of the spectrum. In contrast, emissions from on farm energy use and agrifood systems waste disposal contribute smaller amounts ranging from 2000 to 4000 kilotons over the study period.

Hungary presents a markedly different profile, characterized by higher relative emissions in the food transport and retail sectors compared to its overall emissions scale. Household food consumption remains the largest sources of emissions at 900 kt in 2013. Waste disposal from agrifood system is also a significant contributor, producing between 600 kt and 800 kt of carbon emissions over the study period. Other sources such as food processing, transport, and the retails sector often have emission intensities between 600 and 900 kilotons. Hungary's carbon emissions pattern is more diverse than that of its the larger Western European counterparts.

Italy shows a relatively stable emission pattern with minimal fluctuations. Its emission profile characterized by the contribution of the food processing sector, which is consistently over 8000 kt. The

Table 3

Economic performance drivers in European agricultural systems: Mixed-effects modelling results.

Variables	Coefficient	SE	pValue	Lower	Upper
On farm energy use	0.2828	0.4869	0.5636	−0.6914	1.2570
Agrifood systems waste disposal	−6.1779	24.5240	0.8020	−55.2500	42.8940
Pesticides manufacturing	−2.3013	1.7916	0.2040	−5.8862	1.2837
Food processing	0.1202	0.1490	0.4231	−0.1779	0.4182
Food packaging	0.2754	1.7989	0.8789	−3.3243	3.8750
Food transport	1.8235	0.6737	**0.0089**	0.4755	3.1716
Food retail	0.8443	0.9241	0.3646	−1.0048	2.6934
Household food consumption	0.2992	0.4843	0.5390	−0.6698	1.2682
Sustainable food production	286.09	210.34	0.1790	−134.8	706.97
Renewable energy	−1.4984	7.4817	0.8420	−16.4690	13.4720
Energy efficiency	2622.3	868.09	**0.0037**	885.23	4359.3
Sustainable infrastructure	−1.9334	1.0524	0.0712	−4.0394	0.1725
Food waste	10510	2213.7	**0.0001**	6080	14939
Climate policy	0.0343	0.0298	0.2545	−0.0253	0.0938
Climate education	−8.2334	19.4410	0.6735	−47.1350	30.6680

Note:

- Linear Mixed-Effects Model with REML estimation and country-level random intercepts.
- GDP log-transformed [$\ln(GDP + 1)$] to address skewness and scale issues in dependent variable.
- Random slope for Energy Efficiency included to capture country-specific policy responsiveness.
- Sample: $N = 75$ observations, 5 countries, 15-year period (2010–2024).
- Statistical significance: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$ (bold formatting indicates significance).
- Large coefficient magnitudes reflect log-transformation of dependent variable.
- Model diagnostics include residual plots, normality tests, and heteroscedasticity checks.
- CI represents 95 % confidence interval bounds for each coefficient.
- Economic interpretation requires back-transformation for policy analysis.

Table 4
Water security determinants in EU farming systems: Mixed-effects regression analysis.

Variables	Coefficient	SE	***p*-Value**	Lower	Upper
On farm energy use	0.0007	0.0007	0.3316	−0.0007	0.0020
Agrifood systems waste disposal	−0.0036	0.0341	0.9162	−0.0719	0.0647
Pesticides manufacturing	−0.0029	0.0025	0.2473	−0.0080	0.0021
Food processing	0.0001	0.0002	0.6876	−0.0003	0.0005
Food packaging	−0.0045	0.0025	0.0811	−0.0095	0.0006
Food transport	0.0017	0.0009	0.0797	−0.0002	0.0036
Food retail	−0.0016	0.0013	0.2166	−0.0042	0.0010
Household food consumption	0.0040	0.0007	**0.0001**	0.0027	0.0054
Sustainable food production	1.6048	0.2953	**0.0001**	1.0139	2.1956
Renewable energy	−0.0429	0.0105	**0.0001**	−0.0639	−0.0219
Energy efficiency	−2.7696	1.2187	**0.0267**	−5.2082	−0.3311
Sustainable infrastructure	−0.0018	0.0015	0.2203	−0.0048	0.0011
Food waste	5.9581	3.1080	0.0601	−0.2609	12.1770
Climate policy	−0.0000	0.0000	0.6318	−0.0001	0.0001
Climate education	−0.0447	0.0273	0.1072	−0.0993	0.0100

Note:
- Mixed-Effects regression with random intercepts by Country using REML fitting method.
- Dependent variable: Percentage of population using safely managed drinking water services.
- Random slope for Energy Efficiency captures heterogeneous country-level responses.
- Sample characteristics: 75 complete observations across 5 EU member states.
- Significance testing: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$ (significant results in bold).
- Model specification includes compound symmetry covariance for within-country correlations.
- Negative coefficients for renewable energy and energy efficiency require careful interpretation.
- Water-agriculture linkages operate through complex indirect pathways.
- Confidence intervals (Lower, Upper) provide uncertainty bounds for policy recommendations.

Table 5
Governance stability factors in European agricultural systems: Statistical modelling results.

Variables	Coefficient	SE	pValue	Lower	Upper
On farm energy use	0.0001	0.0001	0.2133	−0.00004	0.0002
Agrifood systems waste disposal	0.0025	0.0021	0.2400	−0.0017	0.0066
Pesticides manufacturing	0.0002	0.0002	0.2218	−0.0001	0.0006
Food processing	0.0001	0.0001	0.2454	−0.0000	0.0001
Food packaging	0.0002	0.0002	0.2207	−0.0001	0.0006
Food transport	−0.0002	0.0001	**0.0014**	−0.0004	−0.0001
Food retail	−0.0001	0.0001	0.6402	−0.0002	0.0002
Household food consumption	0.0001	0.0001	0.8749	−0.0001	0.0001
Sustainable food production	0.0226	0.0226	0.3207	−0.0225	0.0677
Renewable energy	0.0003	0.0008	0.7175	−0.0013	0.0019
Energy efficiency	0.0398	0.0932	0.6709	−0.1467	0.2264
Sustainable infrastructure	−0.0002	0.0001	**0.0464**	−0.0005	−0.0001
Food waste	−0.1453	0.2398	0.5470	−0.6252	0.3346
Climate policy	−0.0001	0.0001	**0.0039**	−0.0001	−0.0001
Climate Education	0.0036	0.0021	0.0969	−0.0007	0.0078

Note:
- Linear Mixed-Effects Model estimated via REML with country-specific random intercepts.
- Political Stability Index ranges from −2.5 (highly unstable) to +2.5 (highly stable).
- Simplified random effects structure (intercept-only) due to bounded nature of dependent variable.
- Cross-country sample: 75 observations from France, Hungary, Italy, Poland, and Spain.
- Statistical significance levels: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.
- Small coefficient magnitudes reflect bounded scale of political stability index.
- Model controls for temporal dependencies through compound symmetry covariance.
- Standard errors (SE) account for clustering within countries over time.
- Policy stability effects may operate through long-term institutional channels not captured in annual data.

household consumption sector shows a gradual transition from higher to lower emissions at around 8000 kt to 5000 kt in 2024. However, the food transport and food retail sectors show a stable pattern of emissions between 4500 kt and 5500 kt from 2010 to 2024.

Furthermore, Spain's emissions depict a stable pattern like Italy, with moderate temporal variations across multiple sectors. The on-farm energy use and food transport sectors are shows a particularly dynamic, with emissions fluctuating between around 5000 and 7000 kt. Food processing emissions of around 6000 kt are significantly higher than packaging emissions of less than 3000 kt. This finding suggests that while packaging contributes to emissions within the EU food system, the predominant source of emissions is likely to be the food processing stage.

Poland's emissions profile is characterised by a distinct stratification across different sectors. It is evident that household food consumption constitutes the primary source of emissions, with an estimated output of approximately 7000 kt. The food processing and food retails sector consistently produces high levels of 4000 kt to 6000 kt of emissions. In contrast, the emissions from pesticides manufacturing and agrifood systems waste disposal sectors were typically below 3000 kt throughout the study period. In addition, there is a gradual shift in the emissions patters of the food retail sector during 2016–2024.

These results highlight the heterogeneous nature of carbon emissions in different European food systems. However, in all selected EU countries household food consumption and food processing are consistently the main contributors to carbon emissions.

To further understand the complex interrelationships from the spatio-temporal contour analysis, it is essential to use a network diagram to quantify the interconnectedness of key drivers and their contribution to carbon emissions.

4.2. Systemic interdependencies among emissions, SDGs, and food security

The network of interdependencies between carbon emissions, SDG targets, and food security (Fig. 3) was constructed using the Pearson correlation coefficient as defined in Equation (8). Each node represents a critical element such as food transport, packaging, sustainable food production, and energy efficiency, with the lines connecting them illustrating the strength and direction of their correlations, as indicated by the r values and their corresponding significance levels. The legend system categorizes correlations by strength and direction: dark red lines indicate strong positive correlations ($r > 0.7$), orange lines represent moderate positive correlations ($0.5 \leq r \leq 0.7$), blue lines show moderate negative correlations ($-0.7 \leq r < -0.5$), and dark blue lines denote strong negative correlations ($r < -0.7$).

A significant positive correlation ($r = 0.66$, $p = 0.0001$) between on-farm energy use and energy efficiency highlights the role of modern technologies and renewable energy in optimizing agricultural operations. Investments in energy-efficient practices not only reduce operational costs but also contribute to lowering greenhouse gas emissions, supporting sustainable agriculture. The correlation with sustainable infrastructure ($r = 0.74$, $p = 0.0001$) underscores the importance of advanced irrigation systems, storage facilities, and renewable energy in bolstering energy efficiency. However, increased energy use can also lead to higher food waste ($r = 0.77$, $p = 0.0001$) if production is not properly managed, emphasizing the need for efficient management systems to mitigate waste and ensure sustainability. On the other hand, the negative correlation with climate policy ($r = -0.61$, $p = 0.0001$) suggests that higher energy consumption on farms may hinder compliance with climate policies, stressing the importance of policy support and sustainable farming practices to curb emissions.

The positive correlation between agrifood systems waste disposal and energy efficiency ($r = 0.71$, $p = 0.0001$) demonstrates that energy-intensive but effective waste management practices can enhance overall energy efficiency on farms. The exceptionally strong correlation with sustainable infrastructure ($r = 0.97$, $p = 0.0001$) highlights the role of robust infrastructure in facilitating effective waste management through recycling and composting, reducing environmental pollution. The correlation with food waste ($r = 0.73$, $p = 0.0001$) indicates that efficient disposal systems can handle and transform waste into valuable products like compost, promoting sustainability. However, the negative correlation with climate education ($r = -0.60$, $p = 0.0001$) suggests that the focus on waste management might detract from educational efforts due to resource constraints. Integrating climate education with waste management practices is essential to reinforce sustainability across all facets of agrifood systems.

Carbon emissions from pesticide manufacturing show a positive correlation with energy efficiency ($r = 0.64$, $p = 0.0001$), indicating that efficient production processes can reduce CO_2 emissions and mitigate environmental impacts while reducing operational costs in food production. However, the correlation with food waste ($r = 0.74$, $p = 0.0001$) suggests that increased pesticide use may lead to higher crop yields but also more food waste if not properly managed. The strong negative correlation with climate policy ($r = -0.77$, $p = 0.0001$) highlights the environmental challenges posed by pesticide production and its association with less effective climate policies, emphasizing the need for strengthened climate policies and sustainable pesticide practices to reduce their environmental footprint.

Furthermore, carbon emissions from food processing are positively correlated with energy efficiency ($r = 0.68$, $p = 0.0001$), sustainable infrastructure ($r = 0.86$, $p = 0.0001$), and food waste ($r = 0.72$, $p = 0.0001$), reflecting the critical role of efficient processing methods in minimizing operational costs and environmental impacts. However, while processing more food is associated with more carbon emissions, this process also helps to reduce waste by converting food waste into useful products. Similarly, efficient food packaging shows a positive correlation with food waste ($r = 0.63$, $p = 0.0001$), as proper packaging can protect food during transport and storage, reducing waste and improving food security. However, both food processing and packaging show negative correlations with climate education ($r = -0.51$, $p = 0.0001$) and climate policy ($r = -0.69$, $p = 0.0001$), respectively, suggesting that the operational focus may sometimes overshadow the importance of educational initiatives and policy compliance.

Efficient food transport is crucial for reducing food waste, with a significant positive correlation ($r = 0.87$, $p = 0.0001$), ensuring timely delivery and reducing spoilage. The correlation with energy efficiency ($r = 0.78$, $p = 0.0001$) and sustainable infrastructure ($r = 0.83$, $p = 0.0001$) highlights the role of modern transportation systems in minimizing waste and enhancing efficiency. However, the negative correlations with climate policy ($r = -0.52$, $p = 0.0001$) and climate education ($r = -0.55$, $p = 0.0001$) suggest challenges in aligning transport practices with sustainability goals due to the environmental impact of transportation. Similarly, food retail shows a positive correlation with food waste ($r = 0.50$, $p = 0.0001$), indicating the potential for waste reduction through efficient retail practices, but it also faces challenges with climate policy compliance ($r = -0.60$, $p = 0.0001$).

The correlations between various food system activities and food security variables underscore the importance of efficient agricultural practices in enhancing food availability and economic stability. On-farm energy use, waste disposal, pesticide use, food processing, and transport all show positive correlations with average dietary energy supply (ranging from $r = 0.52$ to $r = 0.81$) and GDP (ranging from $r = 0.56$ to $r = 0.90$), indicating their role in boosting agricultural productivity and improving nutrition. However, the negative correlations with political stability (ranging from $r = -0.55$ to -0.66) suggest that intensified resource use can lead to conflicts, highlighting the need for sustainable practices to enhance political stability.

The intricate relationships between various components of food system activities and their implications for energy efficiency, sustainability, and food security reveal a complex landscape. Addressing these challenges requires a holistic approach that integrates efficient management practices, sustainable infrastructure, policy support, and climate education to foster a resilient and sustainable agricultural sector. These findings emphasize the importance of integrated strategies that balance economic growth, energy efficiency, and climate policy in achieving sustainable development goals, particularly in the context of food security and carbon emissions reduction.

4.3. *Statistical modelling of food security drivers*

After the establishment of potential relationships through network analysis, a more rigorous econometric approach should be adopted using panel regression. The aim of Linear Mixed-Effects Model (LME) analysis to provide more rigorous assessments on how carbon emissions, Sustainable Development Goal (SDG) indicators, and food security are related in the five EU countries. Tables 2–5 present the results of the linear mixed-effects models, estimated according to Equations (9) and (10), which incorporate both fixed and random effects to capture country-level heterogeneity.

Table 2 presents the factor influencing dietary energy supply demonstrate significant relationships between six key variables and dietary energy availability. The coefficient for on-farm energy use (coefficient = 0.0022, $p = 0.0031$) shows a small but positive effect, indicating that increased energy inputs at the farm level slightly enhance the availability of dietary energy. This could be due to improvements in productivity or efficiency, such as better irrigation systems or mechanized farming practices, which lead to higher yields and subsequently more food being available for consumption.

Household food consumption, with a coefficient of 0.0028 and a highly significant p-value of 0.0003, indicates a stronger positive relationship with dietary energy supply. This suggests that when households consume more, dietary energy availability increases, likely reflecting better access to food and more diverse diets within homes. This variable's strong statistical significance highlights the direct role of household consumption patterns in determining food security.

Sustainable food production, with a coefficient of 1.0969 and p-value of 0.0008, emerges as a crucial factor. The positive relationship underscores the importance of sustainable agricultural practices in enhancing dietary energy supply. Such practices may include crop rotation, organic farming, and the use of renewable resources, which ensure long-term productivity and resilience of food systems, thereby contributing to consistent and improved dietary energy supply.

Food waste, which shows a substantial positive relationship (coefficient = 6.8476, $p = 0.0408$), highlights the impact of minimizing waste on dietary energy supply. The large coefficient suggests that reducing waste could significantly improve the availability of food by ensuring that a higher proportion of produced food is consumed rather than lost, thus directly enhancing the dietary energy available to the population.

On the negative side, the coefficients for pesticides manufacturing (coefficient = -0.0057, $p = 0.0350$) and food retail (coefficient = -0.0033, $p = 0.0196$) reflect small negative effects on dietary energy supply. The negative relationship with pesticides manufacturing could imply that excessive use of pesticides may harm environmental health or food safety, potentially reducing the quality or accessibility of food. The negative effect of food retail may indicate inefficiencies or inequalities in the distribution system that could hinder the availability of dietary energy, possibly through higher food prices or unequal access to retail outlets.

Overall, sustainable food production has the strongest impact on dietary energy supply (coefficient = 1.0969), showing that agroecological farming practices are critical for food availability. The large positive effect of food waste reduction (coefficient = 6.8476) reveals that cutting waste could dramatically improve food availability. However, pesticide manufacturing and food retail show negative effects, indicating these current practices may reduce dietary energy supply.

The analysis of dietary energy supply drivers in Table 2 establishes the foundation for understanding food availability within EU farming systems. This represents the first pillar of food security. However, food availability alone does not guarantee food security; economic access remains equally critical. Table 3 therefore shifts the analytical focus from biophysical availability to economic determinants, examining how carbon emission drivers and SDG progress translate into GDP growth and economic outcomes that determine households' and communities' capacity to access available food. This transition from availability to access reflects the complex pathways through which sustainable farming practices must simultaneously ensure adequate production and economic viability to achieve comprehensive food security.

Table 3 examines the role of different factors in determining Gross Domestic Product (GDP), and the results underscore the interconnectedness between food systems, energy use, and economic performance. Food transport was positively related to GDP (coefficient = 1.8235, p = 0.0089). This positive impact of food transport suggests that efficient logistics improves economic performance by improving food distribution, reducing losses, and supporting market integration. Similarly, energy efficiency emerged as a highly significant driver of GDP growth (coefficient = 2622.3, p = 0.0037), reflecting the importance of energy-efficient technologies in boosting economic productivity. These findings highlight the potential for energy-saving practices not only to reduce energy costs but also it increases productivity and promote sustainable economic development. Another interesting finding was the relationship between food waste and GDP, which was positive and significant (coefficient = 10510, p = 0.0001). At first glance, this result may seem inconsistent and contradictory. However, addressing waste can lead to significant economic benefits, probably by optimizing resource use and reducing the costs associated with waste management. This phenomenon underscores the complex relationship between economic growth and environmental impact.

Overall, energy efficiency emerges as the strongest GDP driver (coefficient = 2622.3), demonstrating that energy-saving technologies boost economic growth. The positive food waste coefficient (10,510) shows that addressing waste creates significant economic value. Food transport also positively impacts GDP, highlighting the economic importance of efficient distribution systems.

Moving beyond the economic pathways linking sustainable farming practices to food access as demonstrated in Table 3, a complete understanding of food security requires an examination of its third pillar, food utilization. This analysis necessitates a focus on the quality and safety dimensions of food consumption. Central to food utilization is access to safe drinking water, which directly affects nutrient absorption, food preparation safety, and overall public health outcomes. Table 4 therefore investigates how the same carbon emission drivers and SDG implementations that influence economic access also shape water access dynamics, recognizing that sustainable agricultural practices have cascading effects on water quality and availability that ultimately determine whether accessed food can be safely utilized for optimal nutritional outcomes.

Table 4 on access to safe drinking water further reveals the complex dynamics between environmental and socio-economic factors. Household Food Consumption reveals a positive and statistically significant relationship (coefficient = 0.0040, p-value = 0.0001). This indicating that increases in food consumption are associated with improve access to safe drinking water. Sustainable Food Production also has a significant positive impact, (coefficient = 1.6048, p-value = 0.0001). This suggesting that sustainable food production practices are strongly linked to improved water safety outcomes.

Conversely, renewable Energy presents a significant negative coefficient of −0.0429 (p-value = 0.0001). Although this result might seem contradictory, but it could reflect complex interactions within the system that require further exploration. Energy efficiency also shows a significant negative association, with a coefficient of −2.7696 (p-value = 0.0267). This relationship suggests that certain energy projects or efficiency measures may inadvertently reduce water availability or quality, highlighting the need for integrated approaches that consider both energy and water sustainability.

Overall, sustainable food production strongly improves access to safe drinking water (coefficient = 1.6048), showing synergies between sustainable farming and water quality. However, renewable energy and energy efficiency show unexpected negative effects on water access, suggesting potential trade-offs that require integrated water-energy planning.

The preceding analyses have established how carbon emissions and SDG progress influence the first three pillars of food security: availability (Table 2), access (Table 3), and utilization through water security (Table 4). The long-term sustainability of these food security outcomes depends on the fourth pillar (stability). This pillar encompasses the sociopolitical conditions necessary for maintaining consistent food security over time. Political stability serves as both a precondition for effective policy implementation and an outcome influenced by resource scarcity and environmental pressures. Table 5 therefore examines how the same systemic drivers that affect food availability, economic access, and utilization also shape political stability, completing the comprehensive analysis of food security's interconnected dimensions within EU farming systems.

Finally, Table 5 of political stability showed how economic and environmental factors intersect to influence governance and social order. Food transport reveals a statistically significant negative relationship (coefficient = −0.0002, p = 0.0014) with political stability. This negative relationship highlights the importance of a stable and efficient food transport contribute to maintaining social stability, such as lower emissions or reduced costs. Similarly, sustainable infrastructure demonstrates a significant negative impact (coefficient = −0.0002, p = 0.0464). This result also underscores the potential for investment in sustainable infrastructure to deliver positive environmental and economic outcomes that can mitigate socio-political unrest. In addition, climate policy was identified as negatively affecting the political stability (coefficient = −0.0001, p = 0.039). This suggest that stronger climate policies help to stabilize political landscapes by addressing the underlying causes of social and political instability, such as a reduction in carbon emissions.

Overall, most variables show minimal effects on political stability, but food transport, sustainable infrastructure, and climate policy have small but significant negative effects. This suggests that stronger policies and infrastructure improvements may initially face political resistance but ultimately contribute to stability.

These results collectively demonstrate the complex relationships between food systems, energy use, environmental policies, and socioeconomic outcomes. As food security, environmental sustainability, and economic growth become increasingly interconnected, these findings provide valuable guidance for policymakers seeking to create resilient, sustainable, and equitable systems.

4.4. SDG-mediated pathways: linking carbon emissions to food security

Investigating the causal pathways between carbon emissions, SDG indicators, and food security outcomes requires a detailed examination. This involves dissecting the contribution of carbon emission sources and assessing how progress towards specific SDG targets acts as an explanatory layer in the observed relationships, thereby revealing the underlying mechanisms. Figs. 4 and 5 display the mediation analysis results, quantifying direct, indirect, and total effects using the OLS regression framework described in Equations (11) and (12).

Fig. 4 presents a mediation analysis exploring how carbon emissions influence various dimensions of food security, examined through different segments of the agrifood system. The analysis covers four critical food security indicators: average dietary energy supply, gross domestic product (GDP), access to safe drinking water, and political stability. Each graph highlights the indirect, direct, and total effects, providing a comprehensive view of how these relationships unfold.

The average dietary energy supply (food availability component) plot in Panel A, among the agri-food system waste disposal (total effect score 0.015) and pesticides manufacturing (total effect score 0.011) have the most substantial total effect on dietary energy supply. This suggests that carbon emissions have a notable impact on this sector, both directly and indirectly, with direct pathways slightly outweighing the indirect ones. Other components, such as food packaging and food retail, also show significant contributions. Their total effects are around 0.005 and 0.003, respectively, indicating their influence on ensuring adequate dietary energy.

In Panel B the effect of carbon emissions on Gross Domestic Product (GDP) (food accessibility component) is most pronounced in the agri-food system waste disposal and pesticides manufacturing sector, where the total effect approaches 21.0 and 14.8. This highlights a strong linkage between carbon emissions and unsustainable agricultural activities through this component. Both direct and indirect effects play significant roles, with direct effects having a moderate edge. Other notable contributors include food packaging and food transport, with total effects of approximately 3.0 and 2.0, respectively, underscoring their economic relevance.

The total effect sizes for safe drinking water (food utilization component) access in Panel C are relatively modest across all agrifood components. Once again, agri-food system waste disposal and Pesticides manufacturing stand out with the highest total effect, slightly around 0.005 and 0.004 respectively, followed by food transport (total effect score 0.0005). The minimal and negative effects observed in other sectors suggest a less direct influence of carbon emissions on this aspect of food security, highlighting the complexity of pathways that ensure safe water access.

The highest negative effects on political stability (a key food stability component) were found to be driven by carbon emissions from agri-food system waste disposal and pesticide manufacturing, with total effects of approximately −0.0004 and −0.0005, respectively. These findings, as shown in Panel D, indicate a generally negative relationship between carbon emissions and political stability. The negative values across all components indicate a slight adverse effect, though the magnitude is relatively insignificant compared to other food security dimensions.

The findings emphasize the critical role of agri-food system waste disposal and pesticides manufacturing in mediating the effects of carbon emissions on key food security indicators, particularly dietary energy supply and GDP. The modest impact on safe drinking water and political stability suggests more complex or indirect influences. This analysis underscores the interconnectedness of carbon emissions and food security, highlighting areas where targeted interventions could mitigate negative impacts and promote a sustainable agrifood system.

While Fig. 4 reveals the direct mediating pathways through which carbon emissions from specific agricultural subsystems influence food security outcomes, a comprehensive understanding of systemic leverage points requires examining how policy interventions through SDG implementation can modify these emission-food security relationships. The carbon emission pathways identified above operate within broader sustainability frameworks where targeted SDG interventions can either amplify or mitigate the observed effects. To complement the emission-focused mediation analysis, Fig. 5 shifts the analytical lens to investigate how progress toward specific SDG targets serves as policy levers that mediate the relationships between agricultural practices and food security outcomes, thereby revealing the intervention pathways through which policymakers can strategically influence the emission-food security dynamics identified in the preceding analysis.

Fig. 5 presents a detailed mediation analysis investigating the interplay between Sustainable Development Goals (SDGs) and various

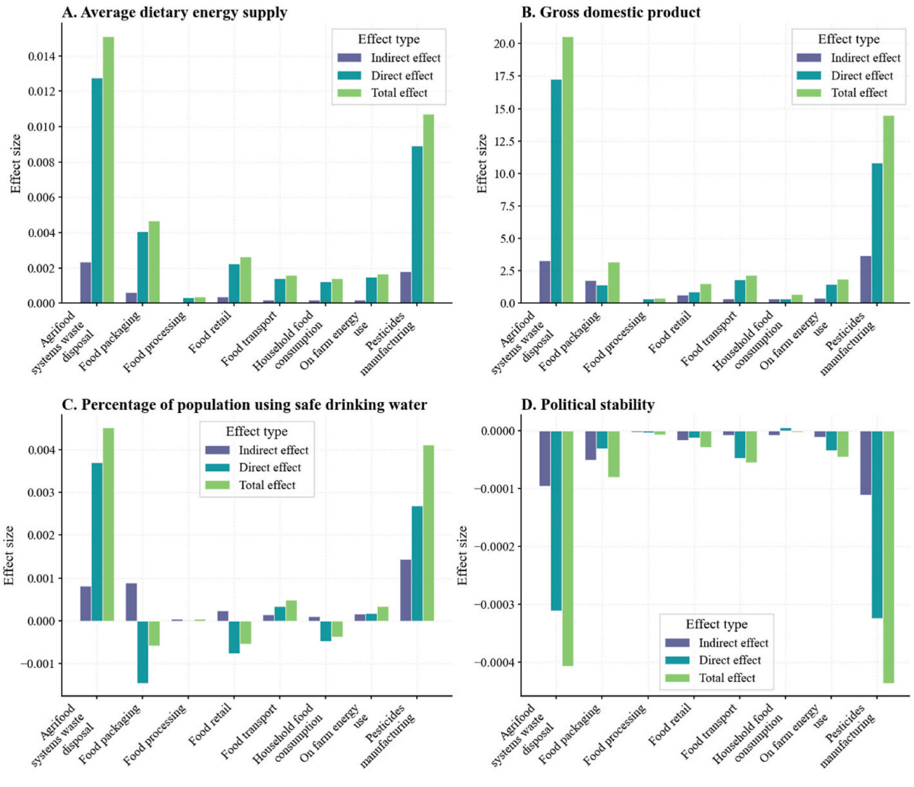


Fig. 4. Mediation pathways in EU farming systems: carbon emission impacts on food security through agricultural subsystems.

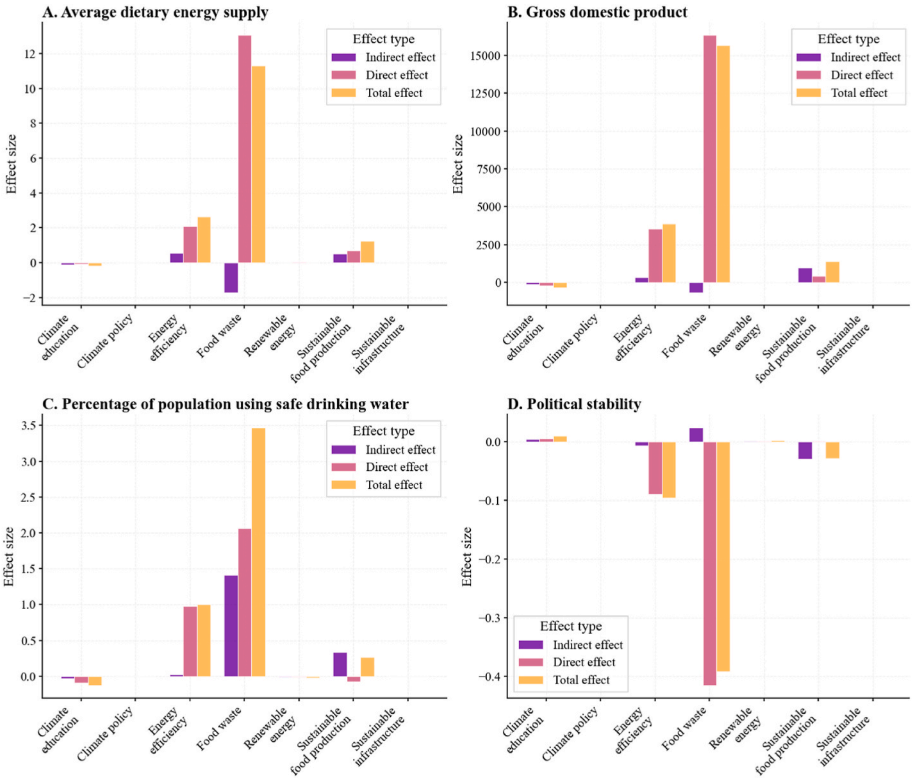


Fig. 5. SDG implementation as mediator between agricultural practices and food security outcomes in EU member states.

food security indicators, mediated by components such as climate education, climate policy, energy efficiency, food waste management, renewable energy, sustainable food production, and sustainable infrastructure. The analysis focuses on four critical food security metrics: average dietary energy supply, gross domestic product (GDP), access to safe drinking water, and political stability. Each subplot captures the indirect, direct, and total effects to illustrate the comprehensive impact pathways.

In average dietary energy supply (component of food availability) plot in Panel A, the food waste (SDG target 12.3) component emerges as a dominant factor, showcasing a total effect size that surpasses 11. This suggests that food waste directly reduces the amount of food available for human consumption, thereby lowering the average dietary energy supply. Indirectly, by minimizing the use of resources (land, water, energy) in food production, it increases the overall availability of food and thus the dietary energy supply. In addition, energy efficiency (SDG target 7.3) shows a moderate total effect, reaching an effect size of approximately 3. This effect is primarily driven by its direct effect, which stands around 2, with a smaller indirect effect of about 1. These values indicate that energy efficiency improves the average dietary energy supply by reducing food production costs, improving agricultural productivity through efficient irrigation systems and precision farming, and ensuring more affordable and accessible nutritious food. In comparison, Climate education (SDG target 13.3) and Sustainable food production (SDG target 2.4) demonstrate insignificant contributions, indicating a lesser direct connection to this aspect of food security.

Similarly, in Panel B Food waste continues to show a significant impact on Gross Domestic Product (GDP) (component of food accessibility) plot, demonstrating a large total effect exceeding 15,500. This effect is composed of a direct effect of around 17,000 and a negative indirect effect of about −1500. This value indicates that food waste diverts economic resources and affects GDP by reducing agricultural and industrial productivity. The total effects of energy efficiency on GDP are a moderate contribute of 3500, which indicating its relevance in reducing operational cost and increase productivity. However, energy efficiency had an indirect impact on GDP through improved resource allocation, job creation in green sectors and long-term economic sustainability. In contrast, climate education, and sustainable infrastructure show minimal overall effects. This indicating limited direct economic impacts through these variables.

In Panel C the total effect of food waste on access to safe drinking water (component of food utilization) is around 3.4, making it as the most influential component in this domain. This highlights a critical linkage between reducing food waste and improving water security. Energy efficiency also makes a significant contribution, with an overall effect close to 1.0. This indicating its role in facilitating access to safe drinking water. Other components like climate education, renewable energy (SDG target 7.2) and Sustainable food production have minimal effects, suggesting a less direct influence on food utilization pillar of food security.

Political stability (Panel D) is a critical precondition for effective food utilization. The impact on political stability (component of food stability) reveals a negative relationship across all components. Food waste showing the most significant total negative effect at around −0.42. This indicates a potentially adverse impact of poor food waste management on political stability. Similarly, energy efficiency has smaller total negative effects, around −0.09. This suggests that their influence on political stability may involve complex or indirect pathways, even though these components are critical for other aspects of food security. Climate education, renewable energy, and sustainable food production display minimal effects, reinforcing the idea of their limited direct impact on political stability.

Overall, these results highlight the significant impact of food waste (SDG target 12.3) on four pillars of food security, particularly in increasing dietary energy supply, GDP, and access to safe drinking water. The negative effects for political stability underscore the complexity of these issues. It emphasizes the need for targeted strategies that address the political and social dimensions of food security. The evidence indicates that the potential of targeted efforts in food waste reduction, renewable energy integration, and sustainable agriculture to not only enhance food security but also address broader economic and infrastructural issues.

Furthermore, to make the findings of the mediation analysis into actionable policy recommendations, a series of country-based scenario analyses must be undertaken.

4.5. Cross-country scenario analysis: SDG-aligned policy pathways to food security

Figs. 6–10 show the scenario analysis outcomes for each country, with projections calculated using Equations (13)–(15) to simulate the impact of 10 % and 20% changes in key variables on food security outcomes.

4.5.1. France: intensive mediterranean system dynamics

The scenario analysis (Fig. 6) for French intensive Mediterranean farming systems reveals distinct patterns of policy intervention effectiveness across multiple food security dimensions.

Panel A demonstrates that energy efficiency interventions show the most substantial impacts on average dietary energy supply, generating positive effects of approximately 0.13 units under 10 % increase scenarios and reaching 0.26 units under 20 % increase scenarios. Conversely, decrease scenarios produce proportionally negative effects of −0.16 and −0.35 units for 10 % and 20 % reductions respectively.

Agrifood systems waste disposal, and Sustainable food production policies exhibit moderate positive contributions in Panel A, with 10 % increases yielding approximately 0.6 and 0.5 units improvement in dietary energy supply, escalating to 0.12 and 0.8 units under 20 % increase scenarios. The remaining interventions, including on-farm energy use, pesticides manufacturing, and renewable energy, demonstrate minimal effects across scenarios, with values rarely exceeding 0.02 units even under favourable conditions.

Transitioning to Panel B, the gross domestic product (GDP) analysis reveals amplified response magnitudes following similar directional patterns. Energy efficiency interventions achieve the strongest positive correlation, reaching approximately 170 units under 10 % increase scenarios and escalating to 290 units under 20 % increase scenarios. Sustainable food production policies contribute positively with values approaching 30 units for 10 % increases and 90 units for 20 % increases. Furthermore, agri-food system waste disposal demonstrates a proportional impact, increasing by 20–40 units in scenarios with 10 % and 20 % increases, and decreasing by a similar amount in negative scenarios. Other intervention categories show negligible economic impacts, suggesting limited immediate GDP effects from these policy levers.

Panel C demonstrates that policy interventions exhibit modest but quantifiable impacts on safe drinking water access in France, with Food Security Impact values ranging from −0.003 to +0.003 across intervention scenarios. This narrow range reflects France's already high baseline water access (98.0–99.4 % from 2010 to 2024, coefficient of variation = 0.007), creating ceiling effects where further improvements are constrained. Agrifood systems waste disposal and Sustainable food production interventions generate the strongest positive correlations, with 20 % increases yielding approximately 0.003 impact units, while corresponding decreases produce similar negative magnitudes. Energy efficiency improvements demonstrate positive associations around 0.002 impact units, suggesting that enhanced energy systems support water treatment infrastructure. Renewable energy interventions show asymmetric responses, with increases producing 0.0015 positive impacts while decreases yield −0.0025 negative impacts, indicating renewable infrastructure's supporting role in water system operations. Carbon emissions-related interventions exhibit more modest effects below 0.002 absolute values. The "Low Variation Impact" annotation accurately characterizes these relationships, where France's near-universal water access limits measurable improvements. However, these quantitatively small impacts represent meaningful changes for the remaining 0.6–2.0 % population lacking consistent access, translating to thousands of individuals gaining improved water access through integrated sustainability policies that simultaneously address agricultural, energy, and water infrastructure systems.

Panel D examining political stability in France's intensive

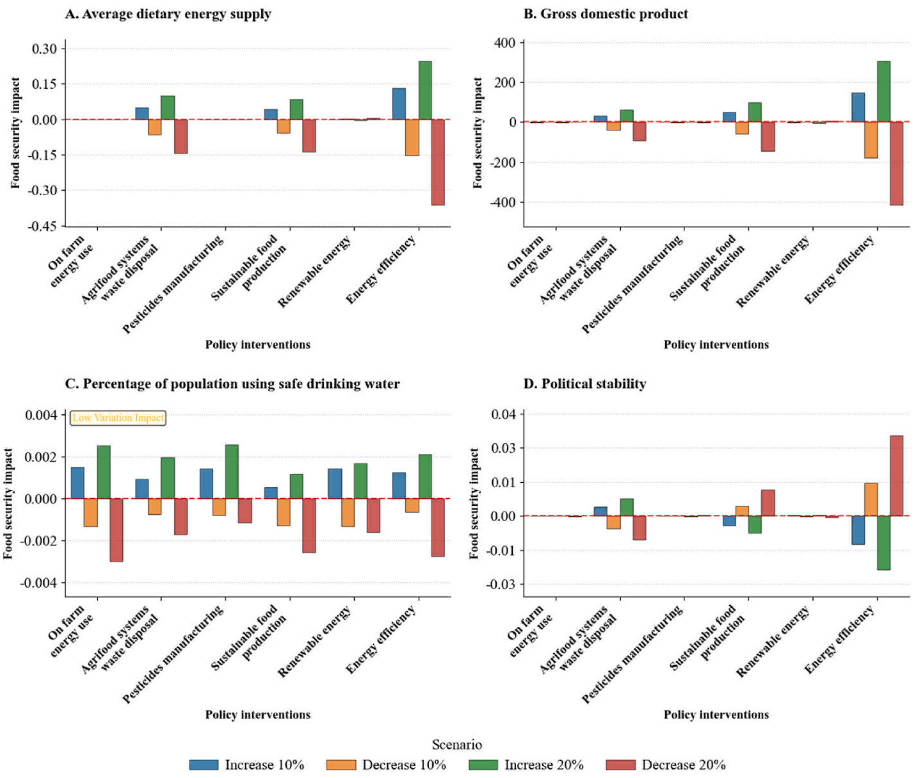


Fig. 6. Farming system scenario analysis: Policy intervention impacts on food security in French intensive Mediterranean systems.

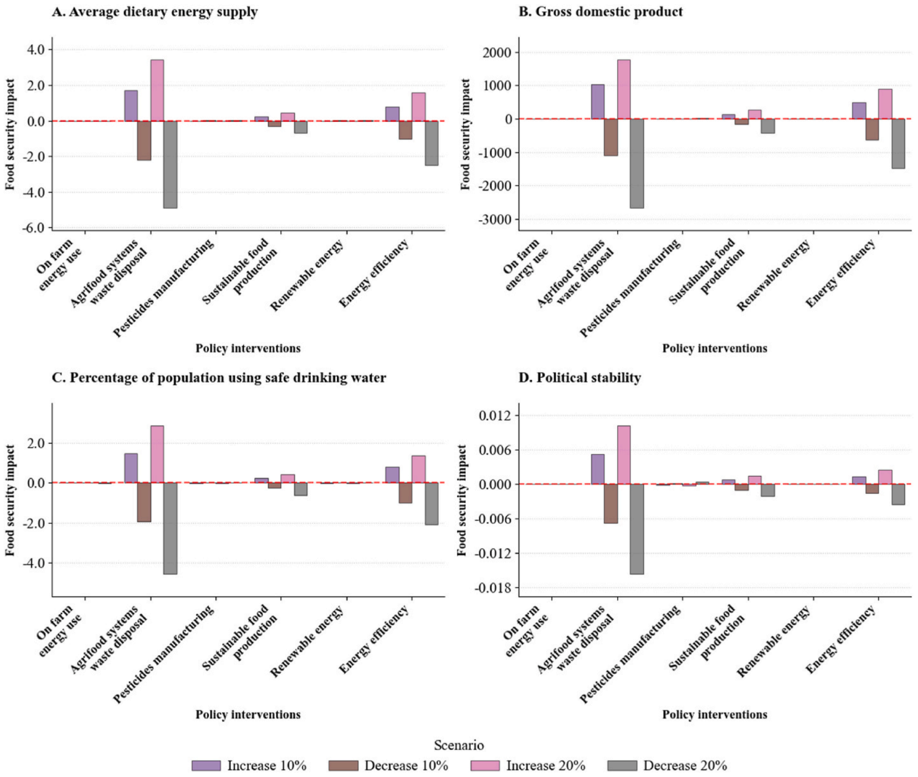


Fig. 7. Farming system scenario analysis: Policy intervention impacts on food security in Hungarian Central European transitional systems.

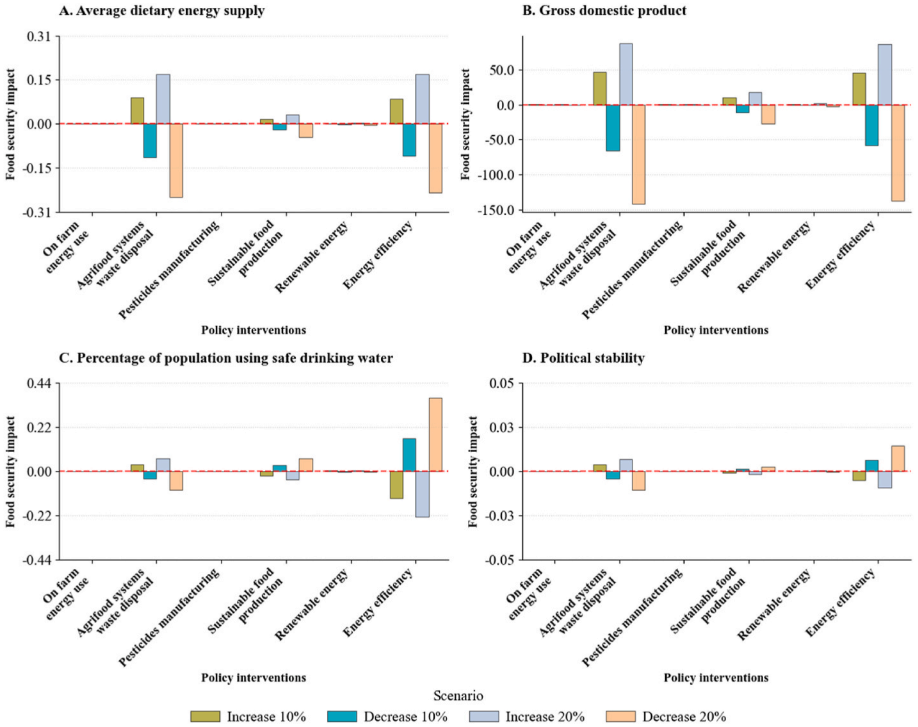


Fig. 8. Farming system scenario analysis: Policy intervention impacts on food security in Italian established agricultural systems.

Mediterranean agricultural system reveals a counterintuitive relationship where energy efficiency interventions demonstrate an inverse correlation with political stability outcomes. Specifically, a 20 % decrease in energy efficiency yields the strongest positive impact on political stability at approximately +0.037 units, while a 10 % decrease generates a moderate positive effect of about +0.016 units. Conversely, energy efficiency increases produce negative political stability impacts, with a 10 % increase resulting in approximately −0.012 units and a 20 % increase leading to about −0.021 units. Sustainable food production follows a similar pattern, where decreases correspond to positive

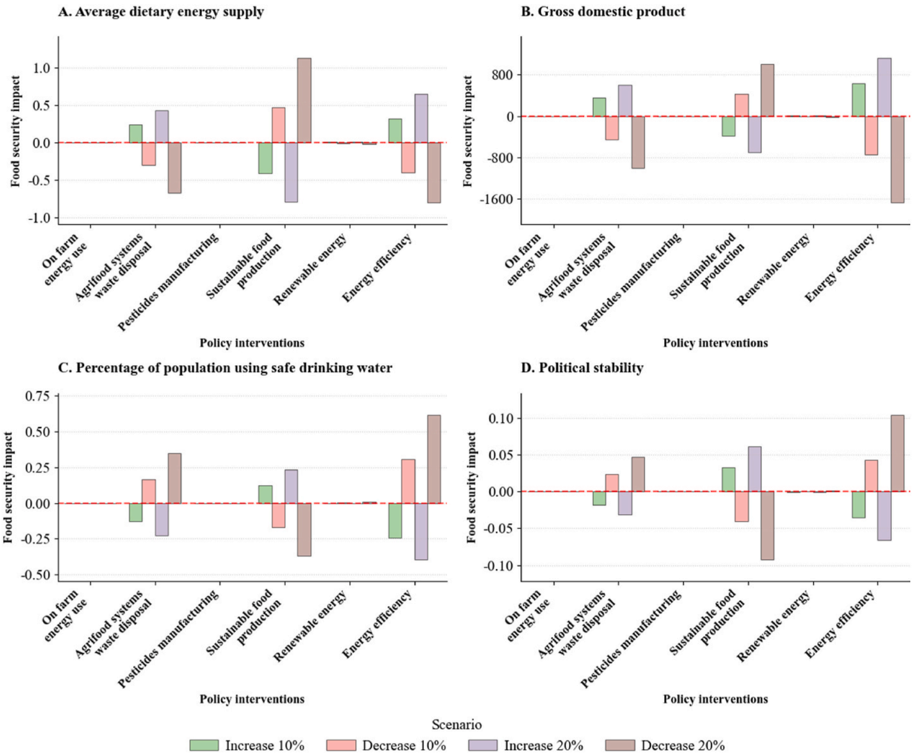


Fig. 9. Farming system scenario analysis: Policy intervention impacts on food security in Polish coal-dependent agricultural systems.

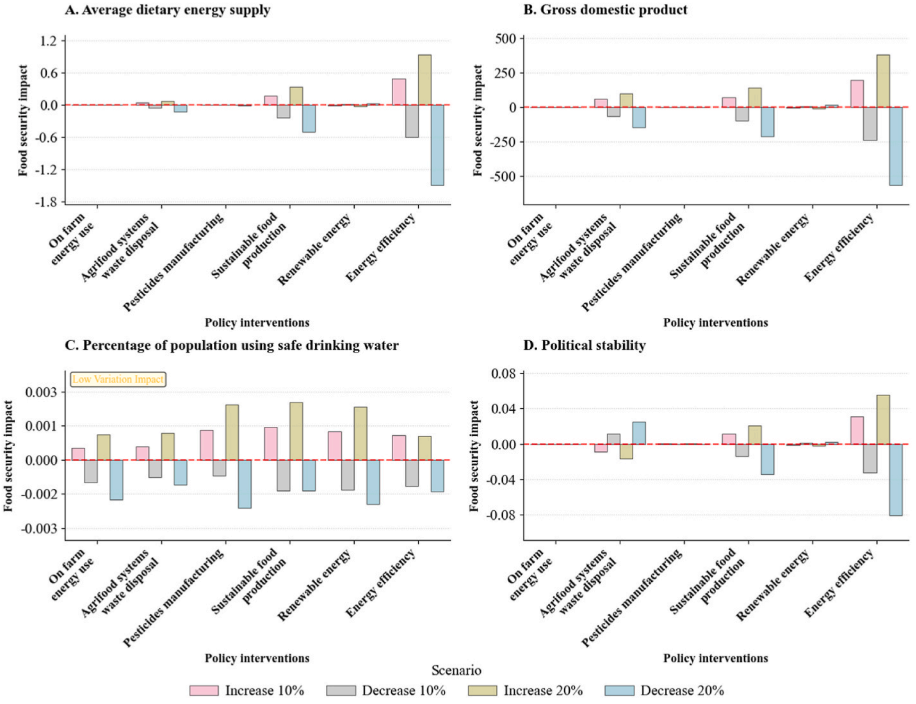


Fig. 10. Farming system scenario analysis: Policy intervention impacts on food security in Spanish Mediterranean bridge systems.

political stability outcomes ranging from +0.005 to +0.011 units, while increases show slight negative correlations. The remaining interventions including on-farm energy use, agrifood systems waste disposal, pesticide manufacturing, and renewable energy demonstrate minimal impacts across all scenarios, with values generally remaining below ±0.005 units. This counterintuitive finding suggests that rapid implementation of energy efficiency measures and sustainable food production practices may initially create social tensions, potentially due to job displacement in traditional sectors, increased costs for farmers, or resistance to technological change in rural communities, highlighting the importance of managing social dimensions alongside environmental objectives during France's agricultural transformation toward sustainability.

The analysis indicates that renewable energy, pesticides manufacturing, and agrifood systems waste disposal interventions produce negligible impacts across all measured indicators compared to energy-focused interventions, suggesting that France's intensive Mediterranean agricultural system exhibits particular sensitivity to energy efficiency improvements while showing limited responsiveness to other policy instruments examined.

4.5.2. *Hungary: Central European transitional economy*

Fig. 7 reveals compelling dynamics within Hungary's Central European transitional economy, demonstrating distinct sensitivities that reflect the unique characteristics of post-socialist agricultural transformation. The analysis compares 10 % and 20 % increases and decreases across six policy interventions, demonstrating differential sensitivities in food security outcomes.

Panel A, examining average dietary energy supply, demonstrates that agrofood systems waste disposal exhibits the most pronounced influence on food security outcomes. Increases of 10 % and 20 % in agrofood systems waste disposal generate approximately 1.8 and 3.5 units of positive impact respectively, while decreases produce substantially greater negative effects of roughly −2.1 and −4.5 units, indicating pronounced asymmetric responses. Energy efficiency interventions show moderate but consistent effects, with 10 % and 20 % increases yielding approximately 1.0 and 1.8 units of positive impact, and decreases resulting in −1.0 and −2.2 units respectively. Sustainable food production demonstrates more modest contributions, with 20 % increases generating approximately 0.6 units of positive impact and decreases producing correspondingly smaller negative effects.

Panel B, analyzing gross domestic product impacts measured in thousands of units, reveals that agrofoods system waste disposal maintains strong influence with 10 % and 20 % increases producing approximately 1000 and 1800 units of positive impact, while decreases generate more substantial negative magnitudes of roughly −1100 and −2600 units. Energy efficiency interventions exhibit moderate responsiveness, with increases of 10 % and 20 % yielding approximately 500 and 800 units of positive impact respectively, and decreases showing proportional negative effects of approximately −500 and −1300 units. Sustainable food production interventions demonstrate relatively limited influence, with 20 % increases producing effects around 200–300 units and decreases generating correspondingly modest negative impacts.

Panel C, measuring percentage of population using safe drinking water, shows agrofood systems waste disposal generating substantial positive effects of approximately 1.6 and 2.5 units for 10 % and 20 % increases, with decreases producing more severe negative impacts of roughly −1.9 and −4.2 units. Energy efficiency interventions display moderate influence, with 10 % and 20 % increases yielding approximately 1.0 and 1.6 units of positive impact, while decreases show proportional negative responses. Sustainable food production maintains modest effects across implementation scenarios, with increases producing small positive impacts and decreases generating correspondingly limited negative effects.

Panel D, evaluating political stability, operates on a smaller numerical scale but maintains proportional patterns. Agrofood systems waste disposal demonstrates 10 % and 20 % increases generating approximately 0.005 and 0.010 units of positive impact, while decreases produce more substantial negative effects of roughly −0.007 and −0.014 units. Energy efficiency interventions show smaller but consistent responses, with increases yielding positive impacts below 0.003 units and decreases producing proportional negative effects. Sustainable food production exhibits minimal influence on political stability, with both increases and decreases generating effects approaching zero across all implementation scenarios.

4.5.3. *Italy: established agricultural system optimization*

Fig. 8 reveals distinctive intervention dynamics within Italy's established agricultural system optimization framework, demonstrating sophisticated relationships between policy measures and multidimensional food security outcomes. This comprehensive analysis illuminates both anticipated and counterintuitive patterns that characterize Italy's mature Mediterranean agricultural economy, where technological advancement intersects with deeply rooted traditional farming structures.

Average dietary energy supply (Panel A), agri-food system waste disposal and energy efficiency interventions exhibit the most pronounced impacts, generating positive effects of approximately 0.1 units under 10.0 % increase scenarios and escalating to 0.16 units under 20.0 % increase scenarios. Corresponding decrease scenarios produce substantial negative impacts of approximately −0.11 and −0.23 units respectively. In contrast, sustainable food production interventions show minimal positive impacts, ranging from 0.02 to 0.03 units in increasing scenarios. They also have minimal negative impacts, with a range of −0.02 to −0.04 units across decreasing scenarios. Meanwhile, on-farm energy use, pesticide manufacturing, and renewable energy all exhibit either minimal or slightly negative effects.

The gross domestic product analysis (Panel B) reveals amplified response magnitudes following comparable directional patterns. Agri-food system waste disposal and energy efficiency policies achieve the strongest positive correlation, reaching approximately 49 units under 10.0 % increase scenarios and escalating to 100 units under 20.0 % increase scenarios. Sustainable food production contributes substantially to positive outcomes, with effects ranging from an increase of 10–25 units in positive scenarios. In contrast, it leads to a reduction of −10 to −30 units in negative scenarios. Other interventions show negligible or slightly adverse effects.

Regarding safe drinking water access (Panel C), energy efficiency maintains its predominant influence with improvements of approximately 0.18 units for 10.0 % increases and 0.39 units for 20.0 % increases. Agri-food system waste disposal and Sustainable food production contributes with positive effects of approximately 0.02–0.04 units, while renewable energy shows smaller positive impacts. Decrease scenarios demonstrate proportionally negative effects across these primary interventions.

The analysis in Panel D demonstrates that policy interventions have a quantitatively small but measurable influence on political stability in Italian farming systems. Energy efficiency shows a counterintuitive, inverse relationship: a 20 % increase correlates with a negative impact of around −0.011, while a similar decrease aligns with a positive impact of about 0.016. Agri-food system waste disposal follows a similar, though less pronounced, pattern. A 20 % increase in waste disposal has a minor positive impact just above 0.008, while a decrease results in a modest negative effect below −0.012. Meanwhile, sustainable food production interventions have minimal impact on political stability, with effects hovering near zero. Overall, the findings highlight the complex and subtle relationships between policy interventions and political stability, which are highly dependent on the established architecture of a farming system.

4.5.4. *Poland: coal-dependent system transformation*

Fig. 9 examines policy intervention impacts on food security indicators within Polish coal-dependent agricultural systems, evaluating carbon emissions and Sustainable Development Goal interventions across four scenarios ranging from 20.0 % decreases to 20.0 % increases applied to six intervention categories. The analysis reveals distinct hierarchical patterns of intervention effectiveness across four key food security metrics.

Panel A reveals that sustainable food production interventions exhibit the strongest positive correlation with average dietary energy supply. A 20 % decrease in these interventions produces the most substantial positive impact at approximately 1.2 food security impact units, while a 20 % increase generates negative effects around −0.8 units. This inverse relationship suggests that reducing sustainable food production policies unexpectedly enhances immediate dietary energy availability, potentially through short-term resource reallocation from long-term sustainability investments to immediate food distribution systems. Energy efficiency interventions demonstrate more moderate positive effects, with 10 % and 20 % increases yielding approximately 0.3 and 0.6 units respectively, while decreases produce corresponding negative impacts.

The analysis of Gross Domestic Product (GDP) in Panel B reveals the economic impact of several policy interventions. Energy efficiency interventions have the most substantial effects. A 20 % increase in efficiency generates a significant positive impact of approximately +900 GDP units, while a 20 % decrease results in a severe negative effect of around −1600 units. This indicates that energy efficiency improvements are a primary driver of economic growth, while a lack of them can severely constrain GDP. Agrifood systems waste disposal policies also show a positive correlation with economic output. When these policies are increased, they have a positive impact on GDP: a 10 % increase yields about +400 units, and a 20 % increase produces around +700 units. Conversely, decreases in these policies generate negative impacts, ranging from −400 to −900 units. This suggests that improved waste management enhances economic productivity through resource recovery and operational efficiency. Sustainable food production policies present a more complex relationship. The analysis shows a mixed but generally negative correlation, as decreases in these policies lead to GDP gains of 400–900 units. This counterintuitive finding suggests that, in some contexts, policies focused on sustainability may impose costs that temporarily hinder economic growth.

In Panel C, energy efficiency interventions show an inverse pattern. A 10 percent increase yields a modest decline in safe drinking water access of about 0.25 units, while a 20 percent increase deepens this decline to roughly 0.4 units. Conversely, a 10 percent decrease improves access by approximately 0.30 units, and a 20 percent decrease produces the largest gain of around 0.60 units. Agrifood systems waste disposal policies exhibit a symmetric but smaller effect. Increasing disposal efforts by 10 percent slightly reduces water access by about 0.10 units, and a 20 percent increase lowers it by roughly 0.24 units. Conversely, reducing disposal by 10 percent boosts access by approximately 0.15 units, and a 20 percent cut raises it by about 0.35 units. Sustainable food production interventions produce intermediate impacts. A 10 percent increase enhances access by around 0.15 units, and a 20 percent increase enhances it by about 0.24 units. In contrast, 10 percent and 20 percent decreases reduce access by roughly 0.15 units and 0.35 units, respectively. This indicates that scaling sustainable production directly influences water infrastructure and quality in parallel with agricultural practice shifts.

In Panel D, political stability responds most strongly to changes in sustainable food production, agrifood systems waste disposal, and energy efficiency interventions. A 20 percent increase in sustainable food production raises stability by about 0.06 units, while a 20 percent decrease lowers it by roughly 0.08 units, indicating that vigorous support for sustainable agriculture bolsters governance and social cohesion, whereas retrenchment undermines political resilience. Agri-food system waste disposal interventions demonstrate moderate effects on political stability. A 10 % decrease in waste disposal improves stability by approximately 0.02 units, while a 20 % decrease yields a larger gain of about 0.05 units. Conversely, equivalent increases generate minor negative shifts, ranging from −0.01 to −0.03 units. This suggests that easing disposal requirements can slightly enhance political stability by reducing regulatory burdens, while tightening them risks mild social friction. Energy efficiency policies display a symmetric but modest inverse relationship with political stability. A 10 % decrease in these policies raises stability by about 0.04 units, with a 20 % decrease yielding a larger gain of 0.11 units. Conversely, 10 % and 20 % increases in energy efficiency reduce stability by roughly −0.03 and −0.07 units, respectively.

This counterintuitive finding may reflect that for some farming systems, a decline in energy efficiency leads to a greater reliance on traditional and less centralized energy sources. This shift could reduce dependency on large-scale infrastructure and centralized systems, which might, in turn, increase local autonomy and public trust. Therefore, the “positive” impact on political stability could be due to a more distributed and locally controlled system, even if it is less energy-efficient.

4.5.5. Spain: Mediterranean bridge system complexity

Fig. 10 reveals the distinctive Mediterranean agricultural dynamics within Spain’s bridge system, demonstrating how policy interventions create cascading effects across multiple food security dimensions while reflecting the unique challenges of managing diverse agro-climatic zones spanning both Mediterranean and continental contexts.

Panel A shows that energy efficiency interventions produce the most substantial impacts on dietary energy supply in Spanish Mediterranean bridge systems, with 20 % increases yielding approximately 1.0 food security impact units and 20 % decreases creating severe negative effects at −1.5 units. Sustainable food production policies demonstrate moderate positive effects with 20 % increases generating around 0.4 units, while agrifood systems waste disposal interventions show consistent positive impacts of approximately 0.1 units for both 10 % and 20 % increases and corresponding negative effects around −0.2 units for decreases. The remaining interventions (on farm energy use, renewable energy, and pesticides manufacturing) exhibit minimal impacts ranging from −0.01 to +0.01 units, indicating their limited influence on dietary energy in Mediterranean agricultural bridge systems.

Panel B demonstrates that energy efficiency interventions produce the strongest economic impacts in Spanish Mediterranean bridge systems, with 20 % increases generating approximately 400 GDP impact units and 20 % decreases creating substantial negative effects around −600 units. Sustainable food production interventions exhibit moderate positive correlations, with 10 % and 20 % increases producing GDP gains of roughly 50 and 125 units respectively, while decreases generate corresponding negative effects, suggesting that sustainable practices enhance economic productivity through improved resource utilization and market access. Agrifood systems waste disposal policies show similar but slightly smaller effects, with 20 % increases yielding about 100 GDP impact units and decreases producing negative impacts of approximately −120 units, indicating that both energy efficiency and sustainable food production investments significantly boost economic output in Mediterranean agricultural systems.

Panel C shows that sustainable food production and renewable energy interventions have the most significant positive impacts on safe drinking water access in Spanish Mediterranean bridge systems. Sustainable food production policies demonstrate consistent positive effects, with both 10 % and 20 % increases producing approximately 0.0025 food security impact units, while 20 % decreases generate the largest negative effect at roughly −0.0025 units. Pesticide manufacturing and renewable energy interventions exhibit similar, albeit subtle, effects on safe drinking water access. Increases in these interventions, whether a 10 % or a 20 % rise, correlate with a small positive impact of approximately 0.0025 units. This suggests that policies promoting these sectors may lead to a slight improvement in water infrastructure. Conversely, a decrease in these policies generates a small negative impact of about −0.002 units, indicating a minor reduction in water access. Energy efficiency policies show moderate positive effects with 20 % increases producing around 0.0008 units while decreases generate negative impacts of roughly −0.002 units, suggesting that efficiency improvements support water system operations but with smaller magnitudes than sustainable production and renewable energy interventions. The remaining policy interventions (on farm energy use and agrifood systems waste disposal) display minimal effects ranging from −0.0005 to +0.0005 units, with a notable “Low Variation Impact” label in Panel C indicating that water access changes are relatively small across all interventions, reflecting the already well-established water infrastructure in Spanish Mediterranean bridge systems where policy changes produce incremental rather than transformational effects on drinking water access.

Panel D reveals that energy efficiency interventions produce the strongest positive impact on political stability in Spanish Mediterranean bridge systems, with 20 % increases generating approximately 0.05 food security impact units and 20 % decreases creating the most severe negative effect at roughly −0.08 units. Sustainable food production policies show moderate positive effects with 10 % and 20 % increases yielding about 0.01 and 0.02 units respectively, while decreases produce negative impacts around −0.01 to −0.03 units, indicating that sustainable agricultural practices enhance political stability through improved rural livelihoods and environmental governance. Agrifood systems waste disposal interventions demonstrate smaller but consistent positive correlations with political stability. A 20 % increase in waste disposal produces a positive effect of approximately 0.025 units, while an equivalent decrease generates a negative effect of roughly −0.02 units. This suggests that policies promoting waste management can contribute to political stability, possibly by enhancing resource security and operational efficiency within the food supply chain. The remaining policy interventions (on farm energy use, renewable energy, and pesticides manufacturing) exhibit minimal political stability effects ranging from −0.01 to +0.01 units, indicating their limited influence on governance outcomes compared to the dominant stabilizing roles of energy efficiency improvements, sustainable production practices, and renewable energy infrastructure in Spanish Mediterranean bridge agricultural systems.

4.5.6. Cross-country synthesis: universal farming system responses

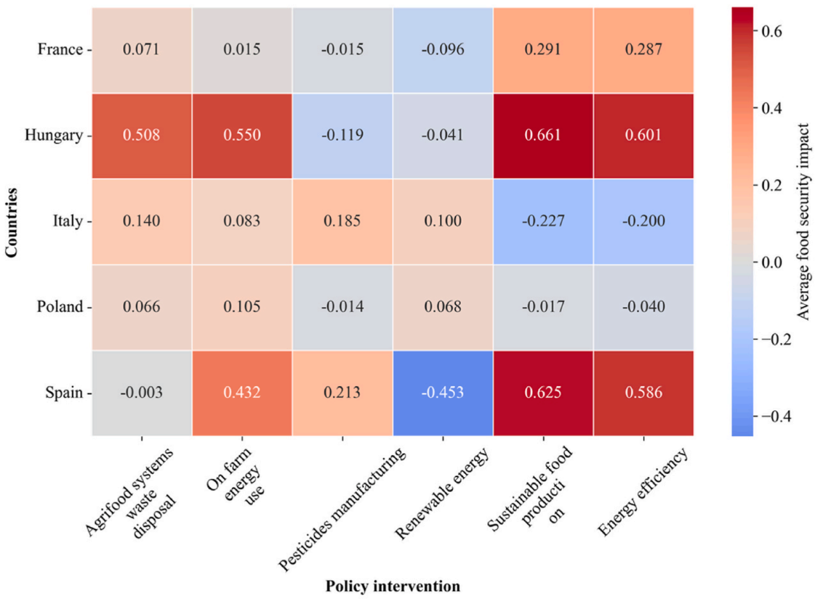
Fig. 11 presents a comprehensive synthesis of policy intervention impacts across five EU farming systems, revealing both country-specific variations and universal effectiveness patterns.

Panel A demonstrates the heterogeneous nature of policy effectiveness across different farming system archetypes, with coefficient values ranging from −0.453 to 0.661, indicating substantial variation in how different agricultural contexts respond to identical interventions.

The heatmap analysis reveals that Hungary exhibits the most pronounced positive responses across multiple intervention categories, with particularly notable coefficients of 0.508 for agrifood systems waste disposal and 0.661 for sustainable food production. These values suggest that Hungary's transitional agricultural system demonstrates considerable potential for policy-driven improvements. In contrast, Spain displays mixed responses, with renewable energy interventions showing a negative coefficient of −0.453, while sustainable food production maintains a positive coefficient of 0.625, indicating intervention-specific effectiveness patterns within Mediterranean bridge systems.

France presents moderate positive responses across most intervention categories, with energy efficiency showing a coefficient of 0.287 and sustainable food production reaching 0.291. These values reflect the established nature of French agricultural systems, where incremental improvements appear more feasible than dramatic transformations. Italy displays an interesting pattern with negative coefficients for sustainable food production (−0.227) and energy efficiency (−0.200), suggesting potential implementation challenges or measurement

A. Policy intervention effectiveness across EU farming system archetypes



B. Universal policy levers: EU-wide intervention impact rankings

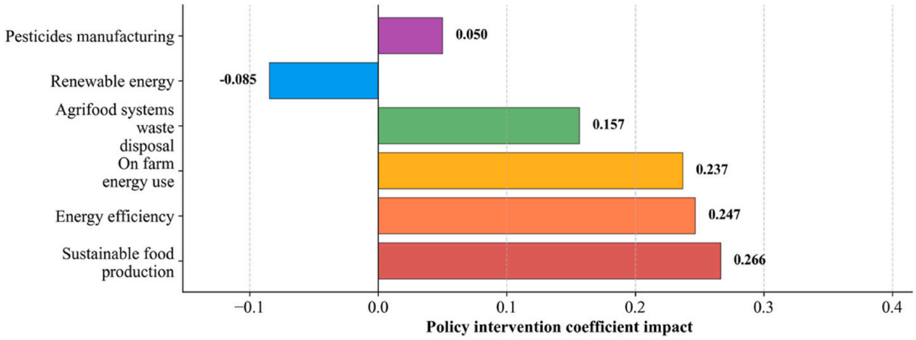


Fig. 11. Cross-country synthesis of policy intervention effectiveness across five farming systems.

artifacts within intensive Mediterranean systems.

Poland demonstrates relatively modest coefficients across interventions, with values generally remaining below 0.105, indicating either limited responsiveness to the measured interventions or the need for different policy approaches within coal-dependent agricultural systems. The country shows positive responses to on-farm energy use (0.105) and renewable energy (0.068), though these remain substantially lower than observed in other countries.

Transitioning to the universal patterns identified across all farming systems, Panel B reveals the relative importance of different policy interventions when aggregated across diverse agricultural contexts. Sustainable food production emerges as the most impactful intervention with a coefficient of 0.266, followed closely by energy efficiency at 0.247. These values suggest that while both interventions demonstrate substantial potential, sustainable food production maintains a slight advantage in terms of universal applicability.

On-farm energy use presents a coefficient of 0.237, positioning it as the third most effective intervention category. This finding indicates that direct farm-level energy optimization measures provide consistent benefits across diverse agricultural systems, though the magnitude remains slightly below that of broader sustainable production approaches. The proximity of these three leading interventions (0.266, 0.247, and 0.237) suggests that effective agricultural sustainability strategies may require coordinated implementation across multiple domains rather than focusing on single interventions.

Agrifood systems waste disposal demonstrates a moderate positive impact with a coefficient of 0.157, indicating meaningful but more limited potential compared to production and energy-focused interventions. This value suggests that circular economy approaches within agricultural systems provide measurable benefits, though these may require longer implementation timeframes or more complex coordination mechanisms.

Pesticides manufacturing shows the smallest positive coefficient at 0.050, suggesting minimal direct impact on the measured food security outcomes despite potential environmental benefits. This finding may reflect the complex pathways through which pesticide reduction influences food systems or indicate that benefits primarily manifest through channels not captured in the current analysis framework.

Renewable energy presents the only negative coefficient at −0.085, indicating potential short-term challenges or trade-offs associated with renewable energy implementation in agricultural contexts. This finding does not necessarily suggest that renewable energy transitions are counterproductive, but rather that immediate food security benefits may not materialize without addressing implementation barriers or temporal lags between investment and returns.

The convergence of patterns across diverse farming system archetypes, as demonstrated in Panel B, provides evidence for coordinated policy approaches while acknowledging the system-specific variations revealed in Panel A. The coefficient magnitudes suggest that effective interventions typically generate modest but measurable improvements, with the largest positive impacts remaining below 0.3, indicating the complex nature of agricultural system transformations and the need for realistic expectations regarding intervention outcomes.

5. Discussion

This investigation into the systemic drivers of carbon emissions within farming systems across five EU countries over the period 2010 to 2024 reveals critical pathways by which Sustainable Development Goal implementation mediates the impacts of agricultural emissions on food security outcomes. The analysis demonstrates that the structural configuration of farming systems, encompassing production intensity, processing infrastructure, and value chain integration, plays a central role in shaping emission profiles and influencing the effectiveness of SDG-oriented interventions. These insights suggest opportunities for optimizing sustainability by targeting leverage points within farming subsystems that concurrently reduce emissions and enhance food security through coordinated SDG pathways.

From the spatiotemporal analysis, three distinct archetypes of farming systems emerge that transcend national boundaries. Intensive processing-dominant systems, typified by France and Italy, show elevated food processing emissions, with Italy consistently exceeding 8000 kt CO_2 annually and France ranging between 5000 and 6000 kt. This pattern reflects the high energy demands of post-harvest operations in these regions, leading to potential inefficiencies and decoupling between upstream production gains and downstream processing emissions. Understanding these dynamics is fundamental to advancing sustainable food systems while meeting environmental goals.

In contrast, transitional consumption-driven systems, exemplified by Hungary and Poland, exhibit more variable emission patterns, with Poland's household consumption sector generating approximately 7000 kt CO_2 and Hungary presenting a more fragmented profile with household consumption around 900 kt alongside significant contributions from transport and retail sectors, each ranging between 600 and 900 kt. These patterns point to less integrated value chains and infrastructural limitations, underscoring the need for tailored approaches in emerging economies. Meanwhile, the Mediterranean bridge system, represented by Spain, displays an intermediate emission profile characterized by fluctuating transport emissions between 5000 and 7000 kt CO_2. This variability likely reflects sensitivity to factors such as fuel price volatility and regulatory shifts, as well as complex supply chain geographies.

Building on these system typologies, mediation analysis highlights the pivotal roles of agri-food waste disposal and pesticide manufacturing as significant mediators linking emissions to food security outcomes. Notably, the SDG 12.3 target on food waste reduction emerges as the strongest mediator, elucidating 21 % of the emission impact on economic outputs such as GDP, with total effects of 21.0 and 15.0 attributable respectively to waste disposal and pesticide sectors. This suggests that managing systemic inefficiencies and chemical inputs is vital in advancing both climate and food security objectives.

Extending these findings, scenario analyses unveil distinct intervention efficacies across countries while identifying universally effective strategies. Aggregated results indicate sustainable food production as the most potent policy lever, with a coefficient of 0.266 reflecting its substantial positive influence on food security metrics across diverse farming contexts. Energy efficiency follows closely with a coefficient of 0.247, reinforcing its centrality in facilitating environmentally and economically sustainable agriculture. The third strongest influence arises from on-farm energy use with a coefficient of 0.237, signifying that direct improvements at the farm level contribute meaningfully to systemic resilience. The proximity of these three leading interventions suggests that effective agricultural sustainability strategies require coordinated implementation across multiple domains rather than focusing on single interventions.

Secondary interventions such as agri-food waste disposal present moderate positive impacts with a coefficient of 0.157, underscoring the value of circular economy approaches, whereas pesticide manufacturing exhibits a modestly positive yet limited association with a coefficient of 0.050. Notably, renewable energy displays a negative coefficient of 0.085, potentially indicating implementation challenges or lagged benefits within current agricultural systems.

Examining country-specific responses reveals considerable variation in policy effectiveness. France's mature intensive system demonstrates sensitivity to energy efficiency enhancements, wherein 10 % improvements correlate with 0.132 unit increases in dietary energy supply and 170 unit rises in GDP. Similarly, Hungary's transitional economy exhibits pronounced sensitivity to agri-food waste management interventions, with increases in this sector generating significant gains in dietary energy provision. Contrastingly, Poland's coal-dependent model reveals counterintuitive patterns where reductions in sustainable food production policies may temporarily enhance dietary energy availability, possibly reflecting short-term reallocations favouring immediate food access over longer-term sustainability investments.

A salient theme emerging across these analyses is the unintended social consequences of rapid technological and policy shifts. For instance, increases in energy efficiency sometimes associate negatively with political stability, with values ranging from 0.001 to 0.012 units across different systems, potentially due to transitional tensions such as labour displacement or costs borne by traditional sectors. This underscores the imperative of managing socio-economic adjustments alongside environmental goals to ensure equitable and sustainable transitions.

Complementary network analysis reveals systemic interdependencies across carbon emissions, SDG indicators, and food security metrics, with strong correlations identified between on-farm energy use and energy efficiency at $r = 0.66$. Concurrently, negative correlations with climate policy compliance at $r = 0.60$ highlight regulatory barriers and the need for harmonized governance mechanisms that accommodate system heterogeneity. These findings address challenges highlighted by Luksta et al. (2024) and Zafeiriou and Azam (2017) regarding the balance between environmental goals and socio-economic factors in EU agricultural systems.

The convergence in policy effectiveness patterns across Mediterranean intensive systems, Central European transitional economies, and bridge agricultural frameworks demonstrates relationships that extend beyond national boundaries, policy frameworks, and agro-climatic conditions. The consistent ranking of sustainable food production, energy efficiency, and on-farm energy use as the most effective interventions provides guidance for policy resource allocation while enabling coordinated European responses to climate change and food security challenges, as noted by Debernardini et al. (2025) and Williams et al. (2024). This convergence suggests opportunities for coordinated policy approaches while recognizing the necessity for system-specific implementation strategies that account for local agroecological conditions, institutional arrangements, and socioeconomic contexts.

6. Conclusions

This study employs analytical techniques to explore the complex nexus between food industry emissions, progress towards the Sustainable Development Goals (SDGs), and key food security indicators in five European Union member states. The analysis reveals three distinct farming system emission archetypes across France, Hungary, Italy, Poland, and Spain: intensive processing-dominant systems, transitional consumption-driven systems, and Mediterranean bridge systems. The cross-country synthesis revealed sustainable food production as the most effective universal policy lever (coefficient 0.266), followed by energy efficiency (0.247) and on-farm energy use (0.237), while renewable energy showed implementation challenges (coefficient −0.085) across all farming system archetypes.

This typological framework advances theoretical understanding by demonstrating how farming system architecture fundamentally determines both emission profiles and policy effectiveness, thereby contributing to systems theory applications in agricultural sustainability research. Moreover, this study establishes farming systems as complex adaptive systems where interventions propagate through SDG pathways to influence multiple food security dimensions, extending sustainability transitions theory into agricultural contexts.

Several limitations constrain the interpretation of these findings. Methodologically, this study focused exclusively on CO_2 emissions, potentially underestimating the full climate impact of farming systems by excluding other significant greenhouse gases such as nitrous oxide (N_2O) from fertilizer application and methane (CH_4) from livestock and rice cultivation, which represent substantial components of agricultural GHG inventories. The national-level analytical scope may obscure farm-level heterogeneity and smallholder decision-making dynamics, while the selected countries, though representing major EU agricultural systems, may not fully capture Nordic or Baltic states with distinct agroecological conditions. Additionally, the focus on aggregated data potentially overlooks important local variations and region-specific challenges that could influence policy effectiveness. The variable selection, while comprehensive, may have omitted other relevant factors such as soil organic carbon dynamics, biodiversity indicators, and socioeconomic variables that could influence the emission-food security nexus.

Future research should develop agent-based models to capture micro-macro interactions within farming systems, particularly investigating mechanisms underlying the observed negative correlations between certain sustainable practices and political stability. Priority methodological advances should include: (1) comprehensive GHG accounting incorporating N_2O and CH_4 emissions alongside CO_2 to provide more accurate carbon footprint assessments; (2) integration of additional variables such as soil health indicators, biodiversity metrics, water quality parameters, and farm-level economic indicators to capture the full complexity of sustainable transitions; and (3) development of life-cycle assessment approaches that account for embedded emissions in agricultural inputs and infrastructure. Priority areas include examining farm-level decision-making processes, especially how smallholders balance emission reduction with livelihood security, and extending the analytical framework to include additional EU member states with different agroecological conditions. Understanding why traditional agricultural factors show unexpectedly minimal effects on measured outcomes challenges conventional policy assumptions and suggests the need for re-evaluating current policy priorities. Future studies should also explore the temporal dynamics of emission-food security relationships through longitudinal farm-level panel data and investigate the effectiveness of specific policy interventions through quasi-experimental designs.

This investigation of systemic drivers across diverse EU farming systems provides essential pathways for SDG-aligned food security that simultaneously addresses carbon emission reduction. By examining the interconnected emission patterns in France, Hungary, Italy, Poland, and Spain, this research reveals actionable leverage points within farming system networks that can guide sustainable transitions. As the EU advances toward its 2030 sustainability targets and net-zero objectives by 2050, this study's findings provide evidence-based guidance for coordinated policy interventions that harness systemic interdependencies between emission drivers, SDG implementation, and food security outcomes across diverse European agricultural contexts.

Data availability statement

The data that support the findings of this study are openly available. All datasets were obtained from public repositories, available from the following sources:

- Carbon emissions and food security indicators were obtained from the Food and Agriculture Organization of the United Nations (FAOSTAT; https://www.fao.org/faostat/en/#data/GT and https://www.fao.org/faostat/en/#data/SDGB).
- Sustainable Development Goal (SDG) target data were retrieved from the Eurostat database (https://ec.europa.eu/eurostat/data/database).

All data used are fully open access and can be retrieved directly from the cited sources. No proprietary or restricted datasets were used.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Nomenclature and Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
CAP	Common Agricultural Policy
CFP	Common Food Policy
CH_4	Methane
CI	Confidence Interval
CO_2	Carbon Dioxide
DV	Dependent Variable
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Database
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IV	Independent Variable
KNN	k-Nearest Neighbors
kt	Kiloton(s)
LME	Linear Mixed-Effects (Model)
N_2O	Nitrous oxide
OLS	Ordinary Least Squares
REML	Restricted Maximum Likelihood
ROI	Return on Investment
SDG	Sustainable Development Goal
SE	Standard Error
SES	Socio-Ecological Systems
USD	US Dollars
VIF	Variance Inflation Factor

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