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Assessing positive and negative factors as catalysts for enhancing European food security amidst threats to SDG 2

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ABSTRACT

Food security remains a critical challenge for the European Union (EU) in achieving Sustainable Development Goal 2 (Zero Hunger). Despite extensive research, three key gaps persist: (1) limited understanding of how positive and negative factors interact to shape food security outcomes; (2) insufficient evidence on the mediating mechanisms linking these factors to SDG-2 achievement; and (3) inadequate quantification of country-specific vulnerabilities within perceived food insecurity. This study addresses these gaps by analysing the combined influence of positive factors, such as GDP growth, agricultural investment, and access to safe water and sanitation, alongside negative factors like cereal import dependency, food price inflation, and nutritional imbalances. SEM results reveal GDP growth as a strong positive driver of food security (path coefficient = 0.845), while cereal import dependency (path coefficient = -0.709) and food price inflation (path coefficient = -0.697) exacerbate vulnerabilities. Austria and The Netherlands exhibit high food security levels due to robust GDP growth rates (5.0 % and 4.8 %, respectively), while Hungary and Slovakia face affordability challenges due to slower GDP growth (2.5 % and 2.3 %) and high food price anomalies (+2.7 % CPI deviation). Nutritional imbalances persist across the region, with obesity rates reaching 25.4 % in Hungary and undernourishment peaking at 4.9 % in Slovakia. Agricultural investment emerges as a critical enabler for domestic production (highest score in Czechia: 2.5), while cereal import dependency negatively impacts countries like The Netherlands (dependency rate: 90.3 %). These findings emphasize the need for targeted interventions, including agricultural investment, food sourcing diversification, price stabilization measures, social safety nets, and infrastructure development to enhance resilience and achieve SDG-2.

1. Introduction

Food insecurity is a complex challenge encompassing disruptions in the steady supply of sufficient, safe, and nutritious food, coupled with challenges in accessing and effectively using food for dietary needs. Accessibility refers to the ability to obtain food efficiently, while utilization involves the effective use of available food, which encompasses considerations such as food safety, nutritional value, and cooking skills [1]. In a pertinent study by Sgroi, highlighted that resilient food systems have the capacity to withstand disruptions and maintain consistent food supply [2]. Furthermore, the SDGs, particularly SDG 2, also focus on "Zero Hunger" and prioritize ensuring access to sufficient food for community progress and stability [3]. Conversely, Burchi & De Muro posited that food security depends on the food availability, accessibility, utilization, and stability of food, which are interrelated and reliant on each other [4]. Barrett identified various interlinked sectors as being responsible for ensuring food security, including food and crop production, transportation, research and education, healthcare, infrastructure development, culinary and catering, warehousing, and market dynamics [5]. In this context, the author explicitly stated that agriculture, research and education, healthcare, infrastructure development, economic controlling organizations (such as banks, insurance, and financial organizations), and regulatory bodies need to work together to confirm food security.

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Chen et al. also studied how food sustainability contributes to SDG 2. The authors identified food security as a complex system. They stated that equitable access to food, appropriate utilization and an adequate, nutritious food supply are necessary to maintain food security. A stable food system is also necessary as well as a diverse, plentiful food supply [3]. Other scholars have focused on using domestic materials to ensure sustainable food security. This includes food accessibility, the highest quality, food safety, and the reduction of food loss and waste [6].

However, there are significant gaps in our knowledge of the complex interactions between positive (e.g., dietary energy and protein supply, gross domestic product (GDP), political stability, access to clean water, safe sanitation) and negative variables (e.g., import dependency, prevalence of obesity, undernourishment and severe food insecurity, low share of agricultural in government expenditure, food price anomalies) that influence food security. Therefore, the current research on food security has extensively explored the role of these in the context of selected EU states.

Ensuring food security in the European Union (EU) remains a critical challenge, particularly in the context of achieving Sustainable Development Goal 2 (SDG-2): Zero Hunger. Unlike previous studies that focus on isolated factors such as economic growth, agricultural practices, and trade dynamics [4,7–10], this research integrates both positive and negative indicators into a unified analytical framework, providing novel insights into systemic interactions shaping food security outcomes. Specifically, the extent to which positive factors (e.g., GDP growth, agricultural investment, access to clean water and sanitation) mitigate the adverse effects of negative factors (e.g., food price volatility, import dependency, undernourishment) remains underexplored. Furthermore, existing literature lacks a comprehensive examination of how food security mediates the relationship between these opposing forces and the achievement of SDG-2. Furthermore, current literature frequently overlooks the mediating role of food security in bridging the complex relationship between enabling and constraining factors and progress toward SDG-2. This gap is critical, as food security functions not only as a policy outcome but also as a foundational determinant of socio-economic resilience. The absence of an integrated analytical framework to examine these dynamics limits the capacity of policymakers to design effective interventions aimed at mitigating structural vulnerabilities and advancing sustainable development goals. By addressing these gaps, this study aims to provide a nuanced understanding of how positive and negative factors collectively influence food security outcomes in the EU. It also seeks to uncover how targeted interventions can enhance resilience against vulnerabilities while advancing SDG-2 goals.

Three research questions were formulated to address the existing research gap. For example, RQ1) How do positive and negative factors collectively influence food security outcomes? RQ2) How does food security mediate the relationship between these factors and SDG-2 achievement? and RQ3) To what extent can positive factors offset the adverse effects of negative influences? Addressing these research questions would not only contribute to a deeper understanding of the complex dynamics of food security in Europe but also provide valuable insights for policy makers and stakeholders in developing targeted strategies and interventions to address vulnerabilities and promote sustainable food systems.

This study aimed to assess how positive and negative factors act as catalysts in shaping food security in eight EU countries, analysing their direct and mediated impacts on SDG-2 (Zero Hunger). By assessing the influence of economic stability, agricultural investment, trade dependency, and food price volatility, the research attempted to determine the extent to which positive factors enhance food security and negative factors hinder progress. Furthermore, it also examined the mediating role of food security in linking these variables to SDG-2 outcomes. The ultimate study goal is to provide evidence-based policy recommendations to strengthen food security resilience and mitigate economic and trade vulnerabilities in the EU amidst evolving sustainability challenges.

2. Literature review and hypotheses development

2.1. Food security and SDG-2

The production and consumption of food contributes to food security. Studies have shown that sustainable food production (SFP) and global food security are linked [7,11–13]. Food security has four main components: availability, accessibility, utilisation, and stability. Burchi & De Muro defined food supply stability as having enough food and different options [4]. Guyalo et al. explained accessibility as being able to buy food and using it properly [14]. These are the "pillars" of food security. In this study, however, food supply is conceptualised not only as the availability of food, but also as the accessibility and affordability of dietary energy and nutrients necessary for food security. This is measured by the average dietary energy supply and average protein supply per capita, and affordability indicators such as the consumer food price index and food price inflation. The coexistence of obesity and undernourishment in some EU countries highlights a nutritional paradox, where food availability does not always translate into nutritional adequacy. This imbalance suggests that while calorie-dense but nutrient-poor foods are widely available, dietary diversity remains a critical issue for food security.

The Food and Agriculture Organization (FAO) defined food security as the consistent availability of adequate, safe, nutritious food that enables an active and healthy lifestyle. The concept of food security is complex and affects social and environmental issues [15]. The problem of food insecurity is a major problem for the United Nations' Sustainable Development Goals (SDGs), especially SDG 2, which aims to end hunger. Severe food insecurity is defined as a lack of access to sufficient food for survival, a situation that demands immediate attention. It is important to understand how ensuring food security helps to achieve the goal of eradicating hunger. It is also vital to evaluate both positive and negative effects of food security to achieve SDG 2 targets. These include diet diversity, GDP, political stability, food import dependency, price anomalies, undernourishment, and obesity rates. The prevalence of undernourishment is defined as a lack of calories or micronutrients.

Food security is shaped by a complex interplay of enabling and constraining factors. Economically, countries with higher GDP levels tend to demonstrate improved food availability and accessibility, owing to increased national capacity for agricultural investment, infrastructure development, and food system resilience. Political stability further contributes by ensuring reliable governance, uninterrupted food distribution networks, and institutional support for agricultural policies. Public health infrastructure, particularly access to clean drinking water and adequate sanitation, also plays a crucial role in supporting food security [16–19]. These elements help reduce disease burdens that impair nutrient absorption and overall health, thus reinforcing the population's ability to benefit from available food resources. Adequate protein and caloric intake remain foundational to physical development and nutritional well-being.

Conversely, a reliance on importing staple foods like grains and protein can expose a country to vulnerabilities in the global market. Disruptions in international supply chains or significant price swings can then threaten the availability and affordability of food within that nation. Additionally, a high prevalence of obesity, while seemingly a different issue, can signal underlying problems within the food system, where some segments of the population may overconsume certain types of food while others lack essential nutrients. The persistence of undernourishment reflects systemic challenges in food distribution and access, particularly among marginalized populations. Simultaneously, rising obesity rates may indicate dietary imbalances and reflect broader inefficiencies or inequities within food systems. Moreover, limited governmental investment in the agricultural sector further weakens national capacities to address food insecurity sustainably, particularly in rural and low-income contexts. Insufficient government investment in agriculture can hinder a nation's ability to produce enough food, thereby making the goal of food security more difficult to attain. Sudden fluctuations in food prices pose significant challenges to food security, particularly for vulnerable populations, by undermining their ability to consistently access nutritionally adequate and safe food. Such volatility can exacerbate existing inequalities and increase the risk of dietary insufficiency among low-income households [8,20–22].

Further insights can be gained into the complexities and potential improvements within the food supply chain by evaluating each of these components in turn. Ultimately, such efforts contribute significantly to the achievement of food security for all [9]. In a similar publication, Gil et al. proposed the implementation of educational and awareness-raising activities with the objective of promoting healthy food production, processing, preparation, and consumption [10]. However, Hurduzeu et al. emphasized the necessity of reducing the intervening circumstances that influence food production, loss, and wastage due to climate change [23].

The above evidence supports the identification and selection of several positive factors with direct implications for the four pillars of food security: food availability, accessibility, utilization, and stability. These factors encompass average dietary energy supply, average protein supply, GDP growth, political stability, access to safe drinking water, safe sanitation, and the agricultural share of government expenditure. These variables reflect economic resilience, infrastructural development, and nutritional adequacy, which are critical for achieving SDG-2: Zero Hunger. As a result, the following hypothesis has been proposed:

Hypothesis 1. ***(H1).*** *Positive factors have a significant and direct positive effect on food security.*

Food systems overlap with agricultural systems in terms of food security, encompassing a range of services, technologies, and activities that regulate the manufacturing process, distribution system, transportation facilities, accessibility, food purchase and consumption. It is therefore pertinent that the sustainable food production system and its consumption level be given particular focus to safeguard the food security system [24]. Furthermore, the future attitudes of individuals towards the healthiness and nutritional value of the foods they consume will also play a role.

The above scenarios describe the real challenges in establishing a robust food security system. These challenges have been sparked by intense debates, which were fuelled by uncertainties. The term "food security" is used to describe the production side of the food chain. However, it is also important to consider the consumption side from the demand perspective. The primary considerations revolve around the essential elements that underlie the effects of several possible options for transformation on both food security and the attainment of SDGs. These elements were established at the United Nations Sustainable Development Conferences in 1992, also known as the Earth Summit [25]. Several factors influence food production and consumption, including geographical location, population trends, urbanization, and globalization. Furthermore, socio-economic tradition, background, GDP and income level, food price anomalies and purchase capabilities, customer reaction, religious practices, and culture have an impact on several levels, including national, local, and household scales [26]. Local and regional policies, regulations, and authoritarian plans related to food systems are undergoing changes to align with the sustainable development goals set by federal (or national) and municipal authorities [27].

Moreover, the sustainability of both urban and rural areas may be enhanced by the implementation of efficient food systems. Furthermore, the creation of new employment opportunities, the establishment of new food industries, the promotion of the use of local products the assurance of political stability, and the reduction of cereal import dependency can also contribute to the achievement of proper food security [28,29]. A notable feature of SDG 2 is that the goal and other objectives for progress are inextricably linked and mutually reinforcing [30]. The SDG 2 encompasses both congruence or synergy and trade-offs or contradictions, which have significance from both the national and global perspectives. The achievement of a single objective may simultaneously address several interrelated concerns. The implementation of measures to combat climate change will concomitantly yield benefits in the domains of energy security, public health, ecosystems, and biodiversity [31]. The SDG 2 is inextricably linked to the issue of food security. Consequently, it is of the utmost importance to strive to achieve the targets set out to address these concerns. The initial interpretation of food security encompasses all issues related to food production that align with the SDG 2. This is because it advocates for a comprehensive overhaul of food security systems and acknowledges the pivotal role played by small-scale agricultural producers. SDG 2 encompasses all the targets that eliminate hunger and ensure the availability of food globally (Target 2.1), as well as improving dietary energy and nutritious protein supply by simultaneously lowering all forms of malnutrition (Target 2.2). It is noteworthy that SDG 2 endeavours to achieve advanced sustainable agriculture and enhance the income level of small-scale food producers (Target 2.3) to attain these objectives [32,33].

The objective of food security can be achieved by focusing on production efficiency. This involves optimizing the use of natural resources, minimizing food losses during production and distribution, managing chemicals and waste, attaining sustainability in business practices and food management reporting, accomplishing sustainability in public procurement, and reducing waste generation. Moreover, the rationale for providing subsidies to fossil fuels may extend to both the production process and the act of consumption [23,34]. From the perspective of food security systems, there are numerous interconnections between food production, processing, supply, and consumption. Alterations in dietary patterns, such as an inclination towards increased intake of meat and dairy products, lead to modifications in production choices and domestic material consumption (DMC) in a society that is facing growing resource limitations [35,36]. The intricate connections between food production and consumption patterns and numerous aspects of the food security system must be considered to accomplish the numerous objectives of SDG 2 concurrently. These connections are both favourable and unfavourable.

Consequently, this study also considered the negative factors that have the potential to undermine food security outcomes. This included cereal import dependency, prevalence of obesity, prevalence of undernourishment, prevalence of severe food insecurity, food price anomalies, consumer food price indices, and food price inflation were included due to their potential to constrain food security outcomes. These variables capture systemic vulnerabilities such as reliance on external supply chains, economic instability, and nutritional imbalances that hinder progress toward SDG-2. Based on the preceding discussion, the following hypothesis was formulated:

Hypothesis 2. ***(H2).*** *Negative factors have a significant and direct negative effect on food security and the achievement of SDG-2.*

2.2. Transitions towards SDG-2

In an environment and development-focused research, Visser & Brundtland [37] proposed that transition is essential to providing current demands without compromising future expectations for establishing a long-term food security system. In this context, the present study indicated that a transformation of food security towards SDG 2 is essential for attaining sustainability. This transformation is intended to address the existing challenges that contemporary societies worldwide are encountering due to the incorporation of all categories of environmental conservation, socio-economic stability, and intergenerational equity systems [38]. Other scholars in a similar research area, such as Abbot et al. [39], have proposed that the transition to the attainment of food sustainability through the efficient use of domestic resources is strongly connected to ensuring food security. These interconnecting results yield several benefits, including an increased quantity of food supply, enhanced food accessibility, optimal utilization of food resources, and greater stability and resilience in the food system [40,41]. The primary concern is the disparity in the availability of resources across diverse groups and cultures at the local, regional, and global levels. Consequently, there is a pressing need for comprehensive social changes that include all sectors and magnitudes. Moreover, an excessive amount of domestic material consumption, coupled with a reduced rate of circular material utilization, has a detrimental effect on sustainability [36,42,43]. The initial concept of sustainability was predicated on the assumption that technological innovation, industrial advancement, and manufactured resources would replace natural and biological resources [44].

However, the concept of sustainability presents a novel challenge. It acknowledges that resources around the world are limited and calls for a significant reduction in our overall resource consumption [36,45,46]. It is evident from the novel concept of food security that focusing on agricultural enhancement and food production improvements is insufficient to attain SDG 2 targets [39,47]. Rather than addressing sustainability in a general sense, it is more crucial to prioritize sustainable consumption and production. This can be achieved through the implementation of SDG 12 [1]. The overarching objective of SDG 2 is to achieve sustainable food security, with a specific aim to reduce global food waste per person by 50 % by 2030. This reduction is to be accomplished on two fronts: first, by retail organizations, and second, by individual customers. It is imperative to reduce food losses by enhancing the efficiency of food production management systems and food supply chains. This includes addressing losses occurring post-harvest to ensure the sustainability of consumption and production [48,49]. Moreover, the transformation narrative demonstrated the highest level of alignment with several SDGs, particularly SDG 2. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) outlined the ways in which societal values are evolving towards more sustainable lifestyles, particularly in terms of resource conservation in areas such as food and energy, as well as non-GDP growth [50].

Nevertheless, the combination of severe poverty, limited resources, adequate road, port and rail infrastructure and uneven resource distribution may result in unsustainable use of natural resources and adverse effects on the Gross Domestic Product (GDP). The interrelated variables previously mentioned contribute to higher poverty rates and impede individuals' capacity to develop local approaches to address progressively severe intermittent or persistent scarcities of food, water, energy, and physical security [51–53]. The combination of conventional and indigenous knowledge with contemporary technical breakthroughs has led to the emergence of several pioneering forms of agriculture, including agroecology, agroforestry, organic farming, urban agriculture, transportation, and energy models [54,55]. Each of these measures has the potential to mitigate environmental, atmospheric, and aquatic damage [56]. The implementation of the SDGs has led to an improvement in the quality of life, with a particular focus on the creation of employment opportunities and the reduction of social inequalities [50]. The historical development of ideas about food sustainability has been inextricably linked to the concept of food security. The global discourse was primarily shaped by the tenets of sustainable development [37]. The declaration encompassed several key areas, including sustainable agriculture, sustainable food diets, and sustainable food systems.

Furthermore, in order to enhance food security and achieve the targets set out in the SDGs, it is recommended that a methodical and comprehensive strategy be employed. Agricultural production represents only one aspect of the broader challenge of food security. Other key areas include packaging, transportation, recycling, and waste management. Other significant factors, including the average food supply, food loss, agricultural research and development, agricultural factor income, political stability, extreme food instability, access to safe drinking water, and obesity rates, directly influence the food and nutritional security status of a country [6,56,57]. The achievement of SDG 2 necessitates the development of an interdisciplinary research approach that integrates the principles of sustainable agriculture, climatic change adaptation, GDP per capita, and infrastructure development aspects. In order to achieve a sustainable lifestyle, it is necessary to enhance diet diversity, protein quality, and the prevalence of obesity related to consumption and food production [58–60]. Nevertheless, the implementation of comprehensive plans, agricultural R&D, the execution of sustainable development goals, and the shift towards sustainability will guarantee the effective management and optimal use of natural resources in the production and consumption processes. This will ultimately lead to the attainment of sustainable food security [61]. It was therefore reasonable to propose the following hypothesis:

Hypothesis 3. ***(H3).*** *Food security mediates the relationship between positive and negative factors and the achievement of SDG-2.*

The existing literature on food security predominantly examines individual determinants, such as GDP growth, political stability, and access to resources like clean water and sanitation. These studies provide valuable insights into isolated relationships between specific factors and food security outcomes. However, a comprehensive understanding of food security dynamics requires investigating the relationship between enabling (positive) and constraining (negative) factors. While some research highlights the importance of positive indicators, such as agricultural investment and dietary energy supply, limited attention has been given to how these factors interact with negative influences like cereal import dependency, food price volatility, and severe food insecurity.

Moreover, previous studies often focus on developing regions where food insecurity is more acute, leaving gaps in understanding systemic vulnerabilities within developed economies like the EU [4,7–10]. For example, while GDP growth is recognized as a driver of resilience, its ability to offset risks posed by import dependency or price anomalies remains underexplored. In addition, the mediating effect of food security on the pathway between these identified factors and the attainment of SDG-2 has received insufficient scholarly attention.

This study addresses these gaps by integrating both positive and negative indicators into a unified analytical framework. By examining their combined effects on food security outcomes across EU Member States, this research contributes to a deeper understanding of how enabling factors mitigate vulnerabilities while advancing SDG-2 goals. This approach builds on existing work while providing novel insights into the systemic interactions that shape food security in developed regions.

3. Materials and methods

3.1. Data collection procedures

Seven variables with a positive impact on food security and SDG-2 (average dietary energy supply, average protein supply, GDP, political stability, access to safe drinking water, access to safe sanitation, agricultural share of government expenditure) and seven variables with a negative impact on food security and SDG-2 (cereal import dependency, prevalence on obesity, prevalence of undernourishment, prevalence of severe food insecurity, food price anomalies, consumer food prices indices, food price inflation) were obtained from the FAO database for eight EU countries (Austria, Belgium, Germany, the Netherlands, the Czech Republic, Hungary, Poland, and Slovakia) for the period 2010 to 2023 [62–64]. However, researchers employed k-NN imputation to address the missing data pertaining to 2024 in the dataset. On the one hand, average dietary energy supply was chosen because it helps prevent hunger, supporting a key component of food security and SDG-2. Adequate calorie supply is essential for an active, healthy lifestyle. Consistent and adequate protein supply is an essential measure for food security and SDG 2, as it improves nutritional quality and addresses undernutrition. GDP is also an important factor, as countries with higher GDP can invest more in food security-related infrastructure. Clearly, political stability reduces the risk of disruption and attracts long-term agricultural investment, thus facilitating food security. Access to clean water also reduces waterborne diseases that affect food consumption, directly contributing to improved food security [65]. Effective sanitation reduces health risks, thus contributing to healthier populations and improved food security through better health outcomes [48]. On the other hand, there are several factors that negatively affect food security. For example, dependency on cereal imports was selected because dependence increases vulnerability to food insecurity, especially in times of crisis. High obesity rates can coexist with poor diet quality, indicating potential challenges in food access and diet quality. High rates of undernourishment are a direct indicator of food insecurity and run counter to the SDG-2 goal of eradicating hunger. The prevalence of severe food insecurity is a direct barrier to achieving food security and SDG-2 targets [49]. Inadequate investment in agriculture can undermine food production capacity, making countries less food secure. Finally, price volatility undermines food affordability, a fundamental component of food security.

3.2. Analytical methods

3.2.1. Statistical software and tools

Python (v3.13), MATLAB (R2024b), and SmartPLS 4 were utilized for data acquisition, manipulation, simulation, and analysis. In Python, relevant libraries facilitated data collection and the careful selection of features representing both positive and negative indicators of food security and SDG 2. A multi-step process involving data preparation, dimensionality reduction, and visualization was conducted using Python's analytical tools.

To align methodology with research objectives, statistical techniques were purposefully selected to examine different aspects of food security across eight EU countries. Principal Component Analysis (PCA) identified dominant patterns and reduced dimensionality; Structural Equation Modelling (SEM) quantified direct and indirect effects of economic, social, and environmental factors on food security and SDG-2 outcomes; and mediation analysis explored the interaction pathways of these variables, revealing the impact of economic stability and food price dynamics.

3.2.2. Data preparation and standardization

The data used in this study was acquired from reliable sources, ensuring the inclusion of relevant features that capture key aspects of food security. Feature selection was conducted based on domain relevance and statistical significance, allowing for a comprehensive yet efficient dataset that reflects both positive and negative factors influencing food security.

To address the high dispersion observed across countries for several indicators (as shown in Fig. 2), researchers implemented a comprehensive data preprocessing strategy. First, we examined the data for outliers using uniform QQ plots following the approach recommended by Abdul-Aziz et al. (2020) [66]. Observations with standardized residuals exceeding ± 2.5 were flagged for further investigation, but none were removed as they represented meaningful country-specific characteristics rather than measurement errors.

Data normalization was performed using z-score standardization (Eq. (3)) to ensure comparability across variables with different measurement scales. This transformation converts each feature into a standard normal distribution with a mean of zero and a standard deviation of one. The z-score for each data point was calculated using the formula:

$$Z = \frac{X - \mu}{\sigma} \tag{1}$$

where X represents the original value, μ is the mean of the feature, and σ is the standard deviation. By applying this transformation, all features contributed equally to the analysis, preventing variables with larger magnitudes from disproportionately influencing the results. Standardization was particularly critical for ensuring that indicators such as GDP, political stability, and prevalence of undernourishment were weighted appropriately in subsequent analyses.

3.2.3. Handling missing data with k-NN imputation

Missing data were handled using the k-Nearest Neighbours (kNN) imputation technique, which estimates missing values based on proximity to similar observations. This approach was used for several measures related to food security, such as the average availability of dietary energy, the level of political stability, the Gross Domestic Product, and the percentage of the population with access to clean drinking water.

The practical application of *kNN* imputation involved first identifying missing entries as Not-a-Number (NaN). For numerical data, the standard Euclidean distance was used to judge how close data points were to each other. For data representing categories, the Hamming distance was used. The optimal number of neighbours (k) was selected through cross-validation, with the best-performing value applied to the dataset. The imputed values were calculated as a weighted average of the corresponding feature values from the nearest neighbours, where weights were assigned inversely to the distance.

If sufficient neighbors are available:

$$X_{\text{imputed}} = \frac{\sum w_i X_i}{\sum w_i} \tag{2a}$$

If there are not enough neighbors, use the feature mean:

$$X_{\text{imputed}} = \bar{x}_{feature} \tag{2b}$$

where X_{imputed} is the estimated value, X_i represents the observed values from the nearest neighbours, and w_i is the weight based on the inverse of the distance. If the required number of neighbours was not available, the mean of the respective feature was used instead.

This method preserved the relationships between food security indicators while minimizing data loss. However, k-NN imputation is computationally intensive for large datasets. To optimize performance, Principal Component Analysis (PCA) was applied to reduce dimensionality before performing imputation. Additionally, by applying Winsorization to the outliers present in the food price inflation and consumer food price indices data, the analysis was made more robust and less influenced by these extreme observations.

3.2.4. Exploratory Data Analysis (EDA)

Initially, the mean μ of a set of observations (Fig. 2) was calculated using the following formula:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3a}$$

The i-th observation is denoted by x_i and n is the total number of observations. The KDE, on the other hand provides a nonparametric approach for estimating the probability density function (PDF) of continuous variables. This function describes the probability of encountering a particular value within the data set. The following KDE formula was employed in the analysis:

$$\hat{f}(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i) \tag{3b}$$

All figures displaying statistical results present error bars representing relevant measures of dispersion or uncertainty. For country comparisons (Fig. 2), error bars represent standard deviations across the 2010–2024 period, capturing temporal variability. For statistical analyses (Fig. 6), error bars represent 95 % confidence intervals calculated through bootstrap resampling, indicating the precision and statistical significance of the estimated effects.

3.2.5. PairPlot with Principal Component Analysis (PCA)

The PairPlot shown in Fig. 3, represented by Eq. (4), $\hat{f}(x)$ estimates the probability density at a specific point (x). It incorporates contributions from kernel functions (K_h) cantered at each data point (x_i) and a bandwidth parameter (h) that governs the smoothness of the resulting density estimate. The combination of these techniques enabled a more in-depth analysis of the selected food security and SDG 2 data. In addition, linear regression was used to uncover trends and dependencies, while KDE was used to identify the distributional characteristics of continuous variables.

Identifying patterns in complex datasets is challenging. This study used Scikit-learn and Principal Component Analysis (PCA) to simplify data. PCA finds new sets of variables, called principal components, that show the main differences in the data. The principal components are derived from combinations of the original features and provide a more concise representation. This approach allows analysts to focus on the most significant trends.

PCA's mathematical basis involves calculating eigenvectors (principal components) and eigenvalues (variance) of the standardized data's covariance matrix (Σ), which was computed as follows:

$$\Sigma = \frac{1}{n-1} \times \left(Z^T \times Z\right), \tag{4a}$$

where Z is the standardized data matrix and n is the number of samples. The eigenvectors (v) and corresponding eigenvalues (λ) of the covariance matrix (Σ) were then computed using the following equation:

$$\Sigma \times v = \lambda \times v \tag{4b}$$

The principal components PC were obtained by projecting the standardized data matrix X onto the eigenvectors:

$$PC = Z \times V, \tag{4c}$$

where V contains the eigenvectors, represented by columns. The equations were implemented in the analysis to standardize the data and perform a PCA for dimensionality reduction and visualization. The total variance explained by the PCA is equal to the sum of the eigenvalues.

3.2.6. Structural Equation Modeling (SEM)

In the structural equation model (Fig. 5), the relationships between positive and negative factors, food security, and SDG-2 are assessed quantitatively through latent constructs and their direct and indirect effects. The selection of SEM as our primary analytical approach was guided by its established capacity to simultaneously examine complex direct and indirect relationships among latent constructs while accounting for measurement error [67]. Our specific model specification was informed by prior applications of SEM in food security research by Haque et al. and Stevens et al. [68,69] where similar mediating relationships were examined.

Factor selection within our SEM framework followed a two-stage process: First, we conducted Confirmatory Factor Analysis (CFA) to validate the measurement model for each latent construct (positive factors, negative factors, food security, and SDG-2). The CFA confirmed that our indicator variables adequately represented their respective latent constructs, with factor loadings ranging from 0.42 to 0.85, exceeding the recommended threshold of 0.40 [70].

The hypothesized relationships between latent constructs were established based on theoretical frameworks from Usman et al. and Bux et at which posit that economic and environmental factors significantly influence food security outcomes through direct and mediated pathways [71,72].

In the first stage of the model, the latent variables (positive factors (*PF*) and negative factors (*NF*)) are defined using their respective observed indicators.

The positive factors (*PF*) is formulated as follows:

$$PF = \lambda_1 FS_1 + \lambda_2 FS_2 + \lambda_3 FS_3 + \lambda_4 FS_4 + \lambda_5 FS_5 + \lambda_6 FS_6 + \lambda_7 SDG_2 \tag{5a}$$

The negative factors (*NF*) formulated as follows:

$$NF = \lambda_8 FS_7 + \lambda_9 FS_8 + \lambda_{10} SDG_2 + \lambda_{11} SDG_2 + \lambda_{12} SDG_2 + \lambda_{13} SDG_2 + \lambda_{14} SDG_2 \tag{5b}$$

where λ_i is the factor loading for each observed variable. Positive factors include average dietary energy supply (FS_1), average protein supply (FS_2), gross domestic product (GDP) (FS_3), political stability (FS_4), safe drinking water (FS_5), safe sanitation (FS_6), and agriculture share of government expenditure (SDG_2). Meanwhile, the negative factors are cereal import dependency (FS_7), prevalence of obesity (FS_8), prevalence of undernourishment (SDG_2), prevalence of severe food insecurity (SDG_2), food price anomalies (SDG_2), consumer food price indices (SDG_2), and food price inflation (SDG_2).

The next stage of the SEM specifies the relationships between the constructions. This captures the impact of positive and negative factors on food security (*FS*):

$$FS = \beta_1 PF + \beta_2 NF + \epsilon_1 \tag{5c}$$

where β_1 represents the positive effect of beneficial factors on food security, β_2 denotes the negative effect of detrimental factors, and ϵ_1 is the error term accounting for unexplained variation.

Food security, in turn affects SDG-2 outcomes (*SDG*2):

$$SDG2 = \gamma_1 FS + \epsilon_2 \tag{5d}$$

where γ_1 is the direct effect of food security on SDG-2, and ϵ_2 is the corresponding error term.

The indirect effects of positive and negative factors on SDG-2 arise through their impact on food security. These effects are calculated as:

Indirect effect of positive factor formulated as follows:

$$IE_{PF \to SDG2} = \beta_1 \cdot \gamma_1 \tag{5e}$$

Indirect effect of negative factor formulated as follows:

$$IE_{NF \to SDG2} = \beta_2 \cdot \gamma_1 \tag{5f}$$

The total effects, combining direct and indirect influences, are then determined as:

For total effect of positive factor formulated as follows:

$$TE_{PF \to SDG2} = \beta_1 \cdot \gamma_1 + \delta_1 \tag{5 g}$$

For total effect of negative factor formulated as follows:

$$TE_{NF \to SDG2} = \beta_2 \cdot \gamma_1 + \delta_2 \tag{5h}$$

where δ_1 and δ_2 capture any direct relationships between positive/negative factors and SDG-2 that are not mediated by food security.

3.2.7. Mediation analysis

In the context of mediation analysis (Fig. 6), the process involves three key components: the mediation model, the outcome model, and the total effect equation.

First, the mediation model, also known as the mediator regression, predicts the mediator (M) using the independent variable (X). This relationship is expressed mathematically as:

$$M = \beta_0 + \beta_1 X + \epsilon_M \tag{6a}$$

Here, M represents the mediator, which could be variables such as cereal import dependency, prevalence of obesity, or political stability. X denotes the independent variable, which could be average dietary energy supply, GDP, or access to safe drinking water. The coefficient β_1 quantifies the effect of X on M, often referred to as path a, and ϵ_M is the error term.

The calculation employed the subsequent formula:

$$Cereal\ import\ dependency = \beta_0 + \beta_1 \times \text{Average dietary energy supply} + \epsilon \tag{6b}$$

In this scenario, the effect of average dietary energy supply on cereal import dependency was examined.

Secondly, the outcome model, or dependent variable regression, predicts the dependent variable (Y) using both the independent variable (X) and the mediator (M). This is formulated as:

$$Y = \beta_2 + \beta_3 X + \beta_4 M + \epsilon_Y \tag{6c}$$

In this equation, Y could represent outcomes such as the prevalence of undernourishment, the prevalence of severe food insecurity, or food price inflation. The coefficient β_3 captures the direct effect of X on Y (path c), while β_4 measures the effect of M on Y (path b). The term ϵ_Y is the error component.

The formula applied in this context was:

$$\text{Prevalence of undernourishment} = \beta_2 + \beta_3 \times \text{GDP} + \beta_4 \times \text{Cereal import dependency} + \epsilon \tag{6d}$$

This example analyzes the combined impact of GDP and cereal import dependency on undernourishment prevalence.

Finally, the total effect equation combines both the direct and indirect effects of X on Y:

$$\text{Total Effect} = \beta_3 + (\beta_1 \times \beta_4) \tag{6e}$$

Here, the direct effect is represented by β_3, and the indirect effect, which is mediated through M, is given by $\beta_1 \times \beta_4$. To illustrate with an example:

$$\text{Total Effect} = (\text{Effect of GDP on Prevalence of undernourishment}) + (\text{Effect of GDP on Cereal import dependency} \times \text{Effect of Cereal import dependency on Prevalence of undernourishment}) \tag{6f}$$

These equation captures the combined effect of GDP on undernourishment, both directly and indirectly through cereal import dependency.

3.2.8. Robustness check

To ensure the robustness and reliability of our findings (Table 2), we conducted a series of sensitivity analyses. These analyses were designed to test the stability of the results under different assumptions and configurations.

First, we re-estimated the Structural Equation Modeling (SEM) using alternative estimation methods, including Weighted Least Squares (WLS) and Generalized Least Squares (GLS). This step verified that the results were not dependent on the choice of estimation technique. Second, we performed a Leave-One-Out Cross-Validation (LOO—CV) procedure, systematically excluding each country from the dataset to ensure that no single country disproportionately influenced the overall findings. Finally, we tested alternative model specifications by incorporating different combinations of control variables to confirm the consistency of key relationships identified in the main analysis.

The Leave-One-Out Cross-Validation (LOO—CV) approach involved recalculating path coefficients by sequentially removing one observation (a country) at a time. The recalculated path coefficients, denoted as $\widehat{\beta}(-i)$, are obtained by applying the formula:

$$\widehat{\beta}(-i) = \left(X(-i)^T X_{(-i)}\right)^{-1} X_{(-i)}^T Y_{(-i)} \tag{7a}$$

where $X_{(-i)}$ represents the matrix of independent variables excluding the i^{th} observation, and $Y_{(-i)}$ is the corresponding dependent variable matrix. This process is repeated for each observation, allowing the model to be tested for stability across different subsets of the data.

The goodness-of-fit of the model is then evaluated using the Comparative Fit Index (CFI), calculated as:

$$\text{CFI} = 1 - \frac{\text{Chi} - \text{Square (Model)}}{\text{Chi} - \text{Square (Null Model)}} \tag{7b}$$

The CFI compares the chi-square value of the fitted model with that of the null model, where a higher CFI value indicates a better fit between the model and the data. These equations and procedures are used to assess the stability and generalizability of the model by excluding each data point and observing the changes in the path coefficients and model fit.

3.2.9. Variable selection and justification

variables selected for this study were chosen to comprehensively capture the multidimensional nature of food security, aligning with theoretical frameworks and empirical evidence. Seven positive factors, such as average dietary energy supply, average protein supply, GDP growth, political stability, access to safe drinking water, and safe sanitation, were included for their direct roles in enhancing food availability, accessibility, and utilization. These variables reflect the economic, nutritional, and infrastructural enablers of food security. Seven negative factors, including cereal import dependency, food price anomalies, and prevalence of obesity, were prioritized due to their potential to constrain food security by increasing vulnerability to supply chain disruptions, economic instability, and nutritional imbalances. Additionally, key Sustainable Development Goal (SDG) 2 indicators such as agriculture's share of government expenditure, prevalence of undernourishment, and prevalence of severe food insecurity were incorporated to align the analysis with global objectives for achieving zero hunger.

The selection of these specific variables was guided by three key considerations: (1) theoretical relevance to the four pillars of food security (availability, accessibility, utilization, and stability); (2) empirical evidence from previous studies demonstrating their significant relationships with food security outcomes; and (3) data availability across the selected EU countries during 2010–2024.

Positive factors like GDP growth drive agricultural investment and infrastructure development, while negative factors such as cereal import dependency create vulnerabilities to market disruptions. Similarly, access to clean water and sanitation enhances dietary utilization, whereas food price anomalies undermine affordability for vulnerable populations.

Building on the outlined conceptual framework, the operational measurement of these variables is detailed below. Table 1 presents the food security and SDG-2 progress indicators and their respective measurement methods for the eight selected EU member states.

To assess the impact of sustainable development on food security and to evaluate the impact of SDG 2 indicators on food security, the Food and Agriculture Organization (FAO) databases (accessed in April 2025) were used [62–64]. This paper focused primarily on food security metrics and Sustainable Development Goals 2 indicators provided by the FAO, as these measures are widely used to assess food security. As part of the 2030 agenda for sustainable development, the selected food security variables also demonstrate the integration and evolution of the SDG targets.

Table 1
Key Variables and Indicators Selected for Food Security and SDG-2 progress.

Pillar	Metrics related to	Indicator	Abbreviation	Description	Measurement
Positive Factors: The Building Blocks of Food Security	FS	Average dietary energy supply	avgdiet	The availability of an optimal quantity of calories is of critical importance. This is measured by the average dietary energy supply, which ensures that individuals have the fuel they need for a healthy life.	% of 3-year average
	FS	Average protein supply	avgprotein	Protein is essential for growth and well-being. A good average protein supply nourishes the population.	% of 3-year average (g/cap/day)
	FS	Gross domestic product	GDP	A strong GDP demonstrates a country's power to utilize its resources effectively. This enables wider access to nourishment for its citizens, along with greater financial investment in better agricultural practices.	GDP (% of real change) - period of urban growth
	FS	Political stability	politstability	The absence of political instability allows a country's food production, distribution, and accessibility to proceed with minimal disruption. This stable environment supports individuals in accessing an adequate and nourishing diet.	Score (0–100) 100=best
	FS	Safe drinking water	safewater	Safe drinking water is vital for good health and digestion. It allows people to absorb nutrients from their food effectively, contributing to overall food security.	% of the total population
	FS	Safe sanitation	safesanitation	The availability of adequate sanitation facilities plays a crucial role in the prevention of diseases and health issues.	% of the total population
	SDG 2	Agriculture share of Government Expenditure	agrigovtexpen	A lack of government investment in agriculture can impede food production and make it more challenging to achieve food security.	Score (1–9) 9 = highest
Negative Factors: The Threats to Food Security	FS	Cereal import dependency	cerealimport	A country's reliance on imported cereals renders it susceptible to a range of vulnerabilities. In the event of a disruption to the supply chain or significant fluctuations in prices, there is a risk of a deterioration in food security.	% of 3-year average
	FS	Prevalence of obesity	prevobesity	While obesity is a significant public health concern, in the context of food security, it can be indicative of an imbalanced system. Some individuals may consume excessive quantities of specific foods, while others may lack access to nutritionally adequate options.	% in population (above 17 years)
	SDG 2	Prevalence of undernourishment	prevundernourish	The prevalence of individuals who are unable to access sufficient food supplies is a matter of concern. Undernourishment represents a significant obstacle to food security and overall well-being.	% of 3-year average
	SDG 2	Prevalence of severe food insecurity	prevfoodinsecurity	Severe food insecurity is defined as the lack of sufficient food to sustain life. This is a matter of urgent concern that requires prompt attention.	% of the total population
	SDG 2	Food Price Anomalies	foodprice	The occurrence of sudden fluctuations in food prices can create challenges for vulnerable populations in affording nutritionally adequate food. This creates a precarious situation regarding food security.	Consumer Price Indices (CPI)
	SDG 2	Consumer food prices indices	confoodpricesind	Tracks changes in consumer food prices over time, with the base year set to 2015. It provides a standardized measure to assess the affordability of food, helping to monitor trends in food prices and their impact on food security.	Index Value (2015 = 100)
	SDG 2	Food price inflation	fpinflation	Measures the rate of increase in food prices over a specific period. This indicator helps to evaluate the economic pressures on consumers and the overall stability of the food market, which are crucial for achieving food security and SDG-2.	Percentages (%)

Source: Authors own construction.

Achieving SDG 2 requires a multifaceted approach that addresses the root causes of food insecurity, while building on existing strengths within the food system. Policy interventions that increase agricultural productivity, promote equitable food distribution networks, and incentivize sustainable production practices can play an important role in addressing food insecurity. Moreover, addressing the underlying social and economic determinants of hunger is critical for long-term success. A comprehensive strategy that integrates these elements can pave the way to a world without hunger.

3.2.10. Analytical framework

A comprehensive analytical framework (Fig. 1) is presented in this study to evaluate the complex factors affecting food security in European Union (EU) Member States. This framework analyses the relationships among socio-economic, political, and nutritional indicators to contribute to the attainment of Sustainable Development Goal 2 (SDG-2): Zero Hunger.

The Fig. 1 shows that food security is influenced by a multifaceted set of factors. Positive factors, such as increased dietary energy supply, protein supply, GDP, and political stability, can contribute to improved food security. Conversely, negative factors, such as cereal import dependency, obesity, and undernourishment, can pose significant challenges.

The analytical framework provides valuable insights into the factors affecting food security in the EU. It highlights the need for targeted interventions to address vulnerabilities, such as reducing cereal import dependency and promoting healthier diets. By understanding these relationships, policymakers can develop more effective strategies to achieve SDG-2 and ensure food security for all.

4. Results and discussion

The analysis of food security in the eight EU Member States revealed a complex web of interrelated factors. Fig. 2 provides a comparative

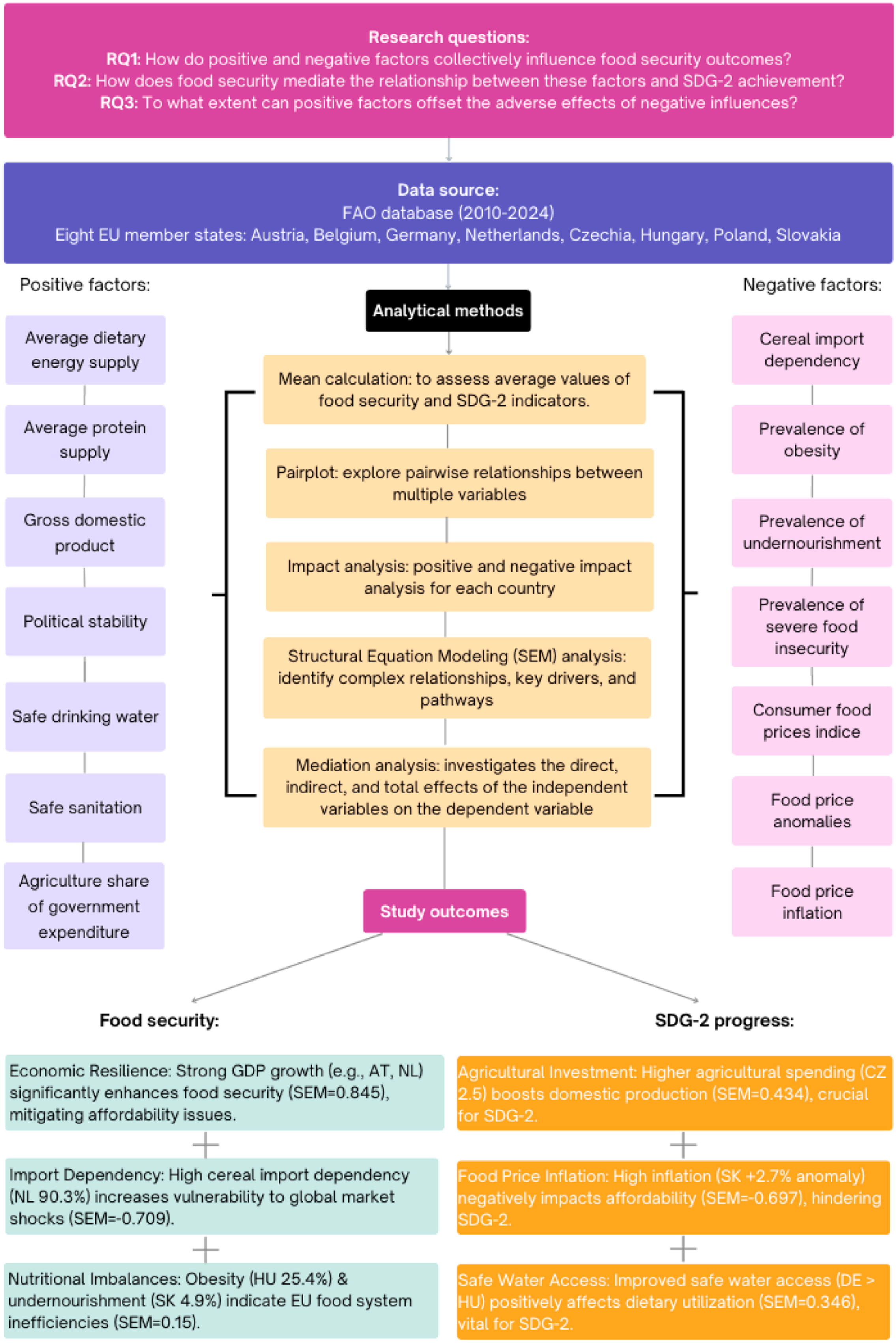

Fig. 1. Analytical framework for assessing food security factors in relation to SDG-2.

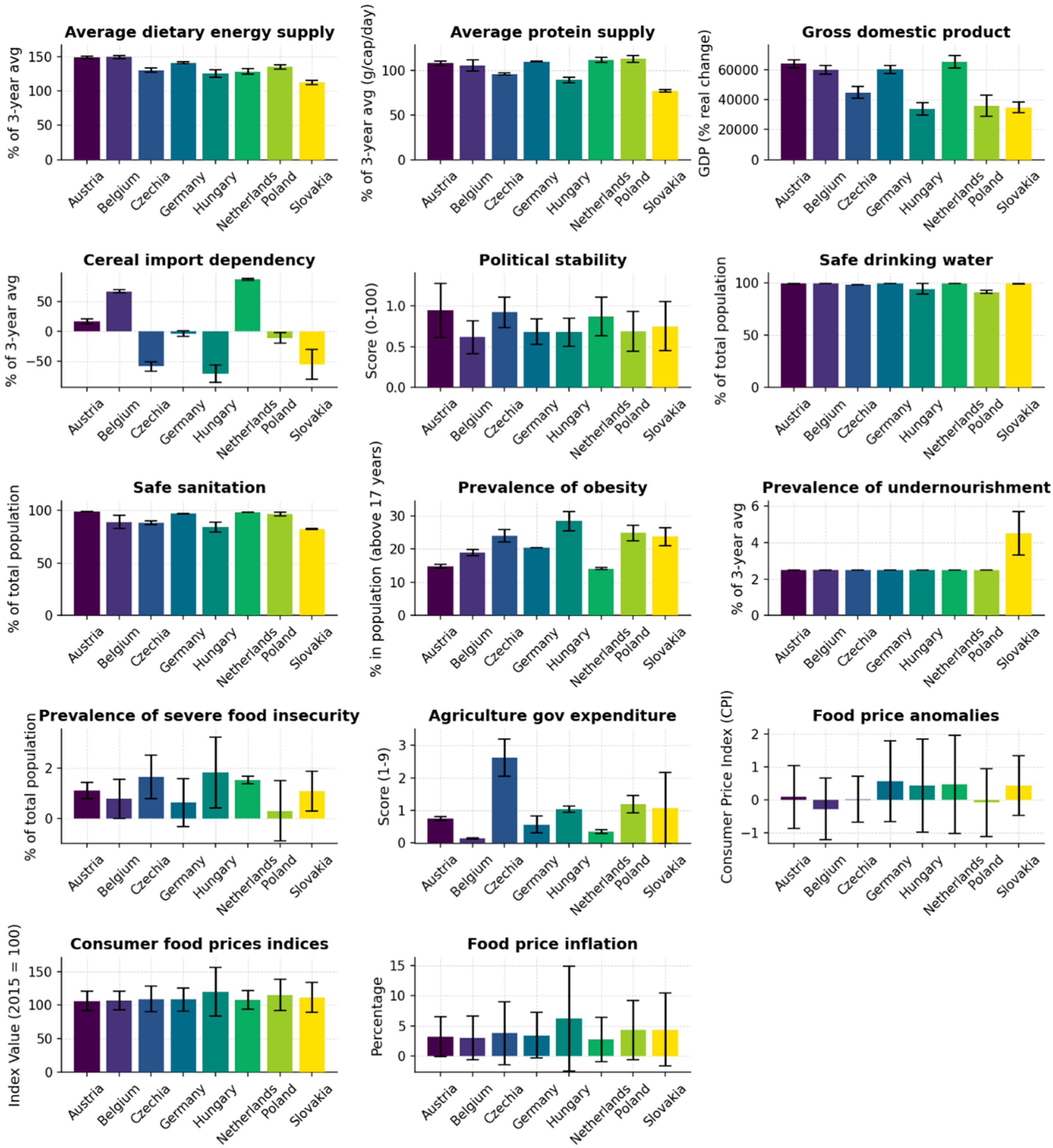

Fig. 2. Comparison of food security levels and SDG-2 indicators across selected EU countries.

assessment of key food security indicators in eight EU countries (calculated using equations 1and 3), highlighting differences in economic stability, food affordability, and diet quality. Error bars in Fig. 2 represent standard deviations calculated over the 2010–2024 observation period, indicating the temporal variability of each indicator within each country. Wider error bars, particularly evident in cereal import dependency and food price inflation indicators, reflect higher year-to-year fluctuations in these metrics.

While this comparison identifies statistical trends between variables such as GDP, dietary energy supply, and food price inflation, the structural interdependencies between these factors are further examined using SEM and mediation analysis in Figs. 5 and 6.

Average dietary energy supply was consistently high in all countries, with Austria, Belgium, Germany, and the Czech Republic at around 145–150 % of the three-year average. Hungary and Slovakia led the way at around 130 %. This indicated a high availability of caloric intake in the selected countries, with minor but notable differences. However, the protein supply was adequate in all countries, with values consistently above 100 % of the three-year average. Austria, Belgium, The Netherlands, and Germany were close to 110 %, while Hungary and

Slovakia had lower values, closer to 90 %, which may indicate dietary differences and lower protein availability. The smaller error bars for this indicator suggest more consistent trends over the years. As a result, the levels of dietary energy and protein supply levels in the selected EU countries were generally above the recommended daily intake for adults (2100–2500 kcal and 50–60 g of protein). This indicated that the food availability, particularly in terms of energy and protein, is sufficient to meet the dietary needs of the population.

Gross Domestic Product (GDP), expressed as a percentage change in current prices, showed considerable variations. Austria and The Netherlands led the way with GDP per capita of almost 60,000 USD, followed by Belgium, and Germany. The Czech Republic was slightly lower, at around 45,000 USD, while Slovakia and Hungary had much lower GDPs, close to 30,000 USD per capita. This economic disparity reflected the different levels of financial resources available to address food security challenges.

Agricultural practices and trade patterns also revealed different levels of dependence on imported cereals. Austria and Belgium had dependencies of around 10 % and 55 % respectively, while The Netherlands had the highest dependency of approximately 60 %. In contrast, the Czech Republic, Hungary and Slovakia were self-sufficient, with negative import dependency values of −60 %. This indicated net exports or minimal dependence on imports. Poland and the Germany were in a lower range, close to −5 %. This reflected the different agricultural capacities and trade patterns of the countries.

Political stability is measured on a scale of 0–1, with most countries scoring between 0.7 and 0.8. These trends underline the diverse socio-political dynamics within the region. Austria, the Czech Republic, and the Netherlands scored higher, around 0.8–0.9, reflecting stable governance and social structures. Meanwhile, Germany, Hungary and Poland lagged behind with scores closer to 0.6. These differences highlighted differences in institutional resilience, which may have implications for food security policies.

Safe Drinking Water was consistently high, with almost all countries scoring between 99 % and 100 % of the population having access. Similarly, safe sanitation remained robust, with coverage ranging from 95 % to 100 % in most countries, underscoring the widespread availability of essential public health infrastructure. In addition, the narrow ranges and minimal error bars suggested universal or near-universal access to sanitation in these countries, reflecting substantial investment in public health infrastructure.

Obesity is a widespread problem among people aged 17 and over in all selected EU countries, with rates generally between 20 and 25 %. Austria, Belgium, and The Netherlands reported obesity rates of around 15–22 % among adults aged 17 and over, while Hungary, the Czech Republic, Poland, and Slovakia had higher rates of over 25 %. This trend reflected differences in dietary habits and lifestyle choices between the selected countries. In addition, these Figures pointed to a common challenge in addressing lifestyle and dietary factors contributing to obesity.

Undernourishment was relatively low across the board, typically below 2.5 %. However, Slovakia stood out with a higher rate of almost 4.4 % of the 3-year average, suggesting potential problems of food distribution or poverty. Severe food insecurity affected a small but significant proportion of the population in most countries, typically between 0 and 2 %. The prevalence of severe food insecurity metric remains minimal, with values close to 1 % in Austria, Belgium, Germany, and Poland. However, Hungary, the Czech Republic, and The Netherlands reported comparatively higher levels of severe food insecurity, with rates around 1.9 %, highlighting inequalities in access to adequate food.

Government expenditure on agriculture varied widely. The Czech Republic allocated the highest share, with a score of over 2.5. Other countries, such as Austria, Germany, Hungary, and Slovakia were moderate spenders with values around 1.0, while The Netherlands and Belgium reported the lowest levels of expenditure, below 0.5. This reflected different national priorities and the size of the agricultural sector.

Food price anomalies measure the disruptions in food prices, which remained relatively low for all countries, averaging close to 1.0 on the index scale. Variations were minimal, with no country exceeding a value of 1.5, suggesting overall stability in food markets. However, Germany, Hungary, and The Netherlands had the highest positive anomaly (consumer price index score of 0.5). This indicator may affect the affordability of and access to food for different population groups.

Consumer food price indices normalised to 2015 as the base year (index = 100) showed slight inflationary trends. Hungary, Poland, and Slovakia reported values close to 125, indicating significant increases in food price since the base year. This reflected moderate food price inflation in these countries over the observed period.

Food price inflation, expressed as a percentage, varied between 0 and 15 % on the y-axis. Higher inflation was observed in Hungary, Poland, and Slovakia, with values of around 4 % to 5.2 %. This pointed to escalating food costs and reflected wider economic pressures that can affect food affordability. Other countries had lower inflation rates around 2.5 %, suggesting less dramatic increases in food prices. Overall, this detailed quantitative assessment revealed different trends and disparities between the selected EU countries. The indicators highlighted strengths in some areas, such as food availability and public health infrastructure, and vulnerabilities in others, including economic disparities, agricultural investment, and inflationary pressures. These findings underscored the need for tailored policies to improve food security and address specific national challenges to achieving SDG-2.

Furthermore, the PCA scatterplots and PairPlots (Fig. 3) helped to understand the relationships between different food security and SDG 2 indicators in the studied European countries. These plots can show interesting patterns or trends that help the understanding of the connections between variables. Data points may show a positive or negative correlation.

The PairPlot with principal component analysis (PCA) (calculated using Eq. (4)) conducted on food security and economic indicators in eight European Union countries revealed key insights into the factors influencing food security, shedding light on both positive and negative elements that contribute to the ongoing challenges and opportunities in achieving SDG 2. The analysis resulted in three principal components, which together explained 67.88 % of the total variance in the dataset.

The first component, referred to as the Food Security and Economic Stability Index, accounted for 34.52 % of the variance, with an eigenvalue of 4.87. This component showed strong positive loadings (ranging from 0.35 to 0.40) for several economic indicators, and in particular, robust correlations with key variables, including loadings of 0.387, 0.404, and 0.390. While PC1 captured most of the variance in food security determinants, it is important to clarify that a high PC1 score does not necessarily indicate a robust food security system. Instead, PC1 represents a dimension that reflects both economic resilience (positive indicators such as GDP and agricultural investment) and potential vulnerability (negative indicators such as high food import dependence and price inflation). A high PC1 score suggests that a country has strong economic potential but may also have structural risks related to external food supply reliance. Conversely, a low PC1 score does not necessarily indicate weak food security but may reflect a reduced dependence on external trade markets.

The second principal component, called the Food Affordability and Price Stability Factor, explained 21.18 % of the variance with an eigenvalue of 2.99. This component showed an interesting mix of positive and negative correlations. It had a notable negative correlation (−0.408) with an economic indicator, while also having strong positive associations with dietary factors (0.522 and 0.406). This suggested a complex relationship between food affordability, price stability, and economic outcomes in the countries analysed.

The third component, identified as Agricultural Investment and Food System Outcomes, accounted for 12.19 % of the variance with an eigenvalue of 1.72. This component was strongly associated with agricultural indicators, as shown by its strong positive loading of 0.625. It

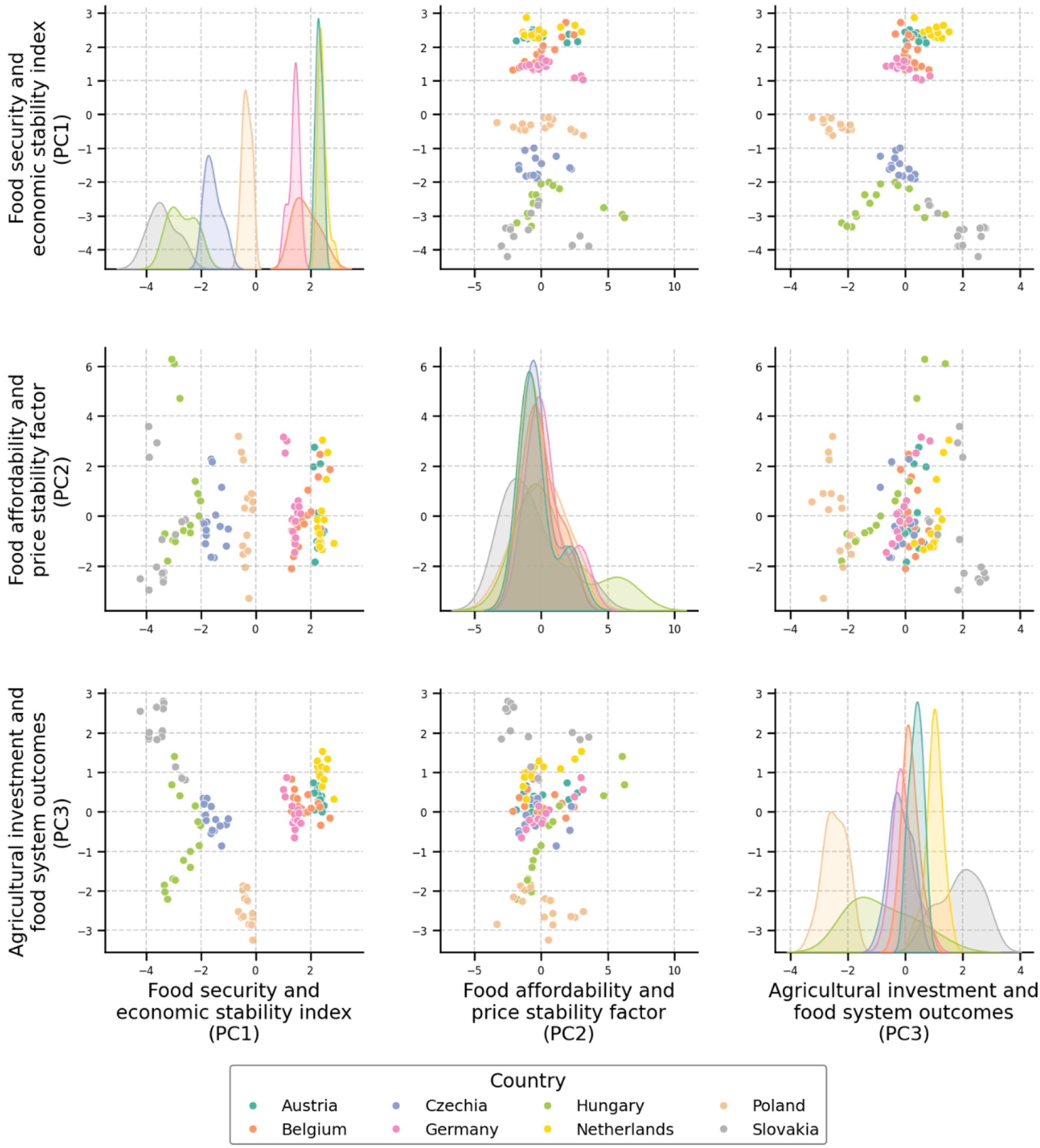

Fig. 3. Assessing catalysts for enhancing European food security: a PCA approach to key economic and agricultural indicators.

also showed moderate positive correlations (0.429 and 0.233) with other measures of economic stability, indicating that investment in agriculture plays a crucial role in ensuring overall economic stability and food security.

The pairwise scatter plots revealed clear patterns of clustering among the countries based on their principal component scores. Countries such as the Netherlands and Germany clearly stood out, positioning themselves in the positive quadrant of both PC1 and PC2. This clustering suggested that these countries have strong economic food security systems and stable dietary conditions. Conversely, countries such as Slovakia were positioned in the negative quadrant of PC1, but their placement along PC2 varied, reflecting the challenges these countries face in their food security systems.

The density plots along the diagonal provided further insight into the distribution of countries along each principal component. The distribution for the "Food Security and Economic Stability Index" (PC1) showed a multimodal pattern, suggesting that countries cluster into different tiers based on their economic food security. The "Food

Affordability and Price Stability Factor" (PC2) displayed a more centrally concentrated distribution with some extreme values, pointing to variations in food affordability and price stability. The "Agricultural Investment and Food System Outcomes" (PC3) showed a slightly skewed distribution with most countries clustered around the centre, but with some outliers indicating differences in agricultural investment and food system outcomes.

These findings underlined the heterogeneity of food security and economic systems across the EU countries studied. The clustering patterns pointed to the need for targeted policy interventions and international cooperation to address the different challenges faced by different countries. The analysis highlighted how economic indicators, food security policies, and agricultural investments are intricately connected and provided a clearer understanding of the unique national characteristics that influence the interplay between these factors.

Examination of the pairwise scatter plots also revealed different groups of countries based on their food security and economic profiles. The Netherlands and Germany consistently showed strong positive scores on the "Food Security and Economic Stability Index" (PC1), with scores clustered between 1.0 and 2.0. These countries showed robust economic food security systems and demonstrated moderate to high values on the "Food Affordability and Price Stability Factor" (PC2), indicating well-managed dietary conditions despite potential disparities. Belgium and Austria formed another group, typically positioned in the moderately positive range of PC1 (0.5 to 1.5) and showing similar patterns in their "Agricultural Investment and Food System Outcomes" (PC3) values. This positioning suggested that these countries maintained relatively stable food security systems, though not as pronounced as the Netherlands and Germany.

Countries such as the Czech Republic showed a more complex pattern, clustering around neutral values in PC1 (−0.5 to 0.5), but with considerable variation in PC2 and PC3, suggesting a more volatile relationship between economic factors, food affordability, and agricultural outcomes. Hungary followed a similar trajectory to the Czech Republic but tended to be more negative values in PC1 (−1.0 to −2.0), which could indicate challenges in terms of economic food security, despite moderate stability in the agricultural economy. Poland, on the other hand, showed a more scattered distribution across different quadrants, with negative values in PC1 and varying positions in PC2 and PC3, reflecting a complex interplay between economic transitions and food security policies.

Slovakia, with the most negative values in PC1 (−2.0 to −4.0), displayed high variability in both PC2 and PC3. This suggested that Slovakia may face significant challenges in terms of food security and economic disparities, although there were indications of some improvements in agricultural stability at certain points.

The diagonal density plots highlighted the country-level patterns and showed clear separations, especially along PC1. The multimodal distribution highlights natural country groupings: high food security performance (Netherlands, Germany), intermediate levels (Belgium, Austria), and significant challenges (Slovakia, Poland, Hungary, the Czech Republic). These patterns were likely to reflect broader economic development trajectories and the effectiveness of food security policies within the EU. Fig. 4 also provided insights into the relative contributions of each country, considering both positive and negative impacts. While some countries demonstrated robust positive performances, others faced challenges that resulted in negative contributions.

However, the positive and negative effects of different countries were expressed in standardized scores. The variables were normalised according to Eq. (1). Subsequently, the sum of the positive and negative impact variables was calculated. Austria demonstrated remarkable resilience, achieving a significant positive sum of 4.8057 and a moderate negative sum of −1.6836. This performance reflects Austria's strengths in food security, driven by positive catalysts such as high dietary quality,

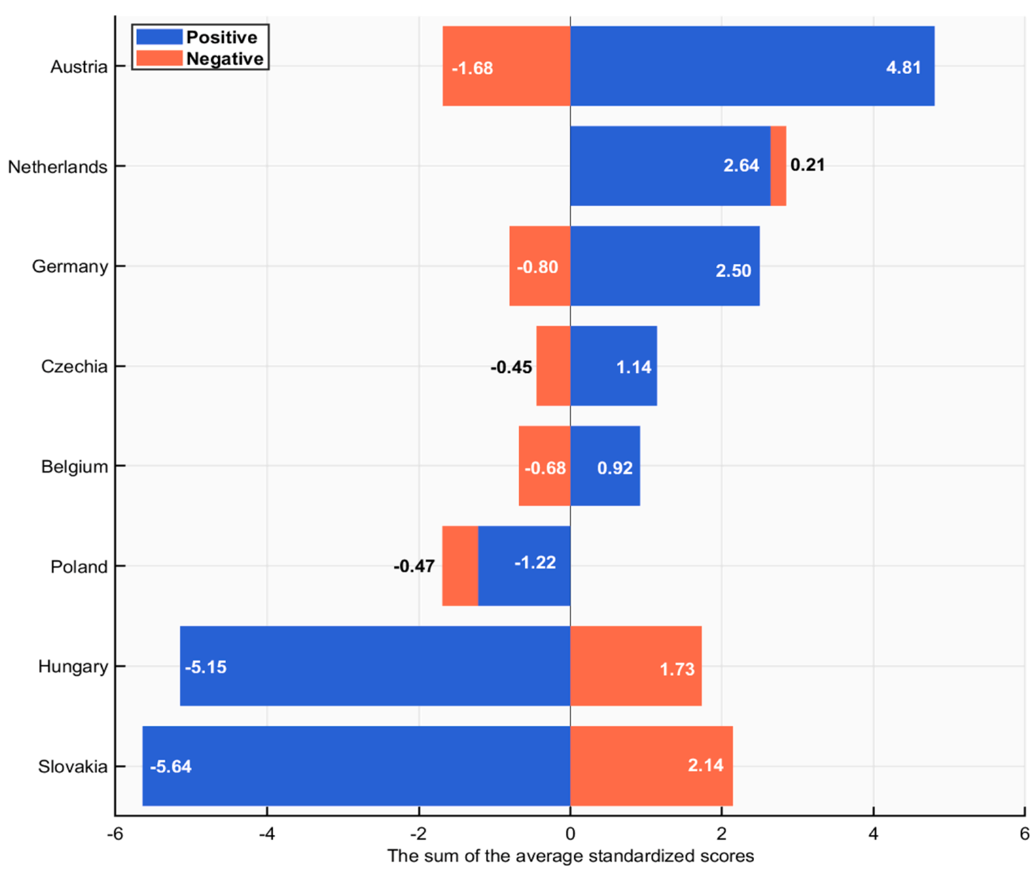

Fig. 4. Comparative analysis of positive and negative impacts for each country.

access to essential resources, and political stability, which effectively outweigh its negative influences. These results position Austria as a leader in advancing Sustainable Development Goal 2 (SDG 2).

Belgium, while performing moderately, recorded a positive sum of 0.9208 and a negative sum of −0.6800. Positive drivers, including dietary standards and economic stability, supported its food security outcomes, though the relatively modest net impact highlights areas where further progress is needed to address vulnerabilities.

The Czech Republic achieved a balanced performance, with a positive sum of 1.1448 and a negative sum of −0.4479. This outcome underscored the Czech Republic's steady progress in food security, though challenges such as limited economic resilience and gaps in agricultural investment slightly dampened its overall contribution.

Germany, as a leading economic power in Europe, reported a positive sum of 2.4987 and a negative sum of −0.8030. Germany's food security outcomes were strongly influenced by positive factors such as robust economic systems and effective governance, outweighing the negative drivers. This highlighted Germany's satisfactory advancement toward SDG 2.

In contrast, Hungary faced significant hurdles with a negative positive sum of −5.1492 and a pronounced negative sum of 1.7336. These results pointed to severe challenges in food security, including limited access to safe water and persistent food insecurity, which undermined Hungary's overall progress and regional contributions to SDG 2.

The Netherlands emerged as a strong performer, with a positive sum of 2.6402 and a minimal negative sum of −0.2082. Positive factors, such as robust economic indicators and efficient systems, had positioned The Netherlands as a major contributor to regional food security resilience and SDG 2.

Poland recorded a negative positive sum of −1.2171 and a negative sum of −0.4721. While Poland faced challenges in areas such as economic stability and infrastructure, its efforts in agricultural investment and food price stabilisation helped to mitigate some of these negative influences, although not enough to achieve a net positive outcome.

However, Slovakia struggled with significant vulnerabilities, reflected in a negative positive sum of −5.6439 and a substantial negative sum of 2.1448. Persistent challenges such as economic underperformance and limited access to critical resources exacerbated Slovakia's difficulties in achieving food security and SDG 2 targets.

Overall, these findings provided empirical support to the second hypothesis (H2), which suggested that an association exists between positive factors (such as GDP, political stability, access to sanitation, etc.) and negative factors (like high cereal import dependency, prevalence of undernourishment, etc.) in determining food security outcomes and the achievement of SDG-2. Countries with stronger economic systems and governance, such as Austria and The Netherlands, demonstrated higher resilience, while those facing structural challenges, like Hungary and Slovakia, showed weaker results. These insights emphasized the necessity of targeted, country-specific interventions to address vulnerabilities and enhance regional food security amid threats to SDG 2.

In addition, the study used structural equation modelling (SEM) and mediation analysis to provide a more complete picture of the relationships between variables. Fig. 5 visually represents the direct, indirect, and mediating effects, showing how food security is influenced by economic and social determinants. These models enhanced the interpretability of the results and ensured that complex interactions are better understood.

Fig. 5 provides a detailed SEM analysis (calculated through Eq. (5)) of the factors influencing food security and their contributions to achieving Sustainable Development Goal 2 (SDG-2). It outlines the relationships between latent constructs such as positive and negative factors and their direct and indirect effects on food security, which serves as an intermediary link to SDG-2. The strength and direction of these relationships are indicated by coefficients, enabling a quantitative understanding of these dynamics.

Interestingly, positive factors had a significant and negative relationship with negative factors (coefficient = −0.596, p = 0.001), indicating that improvements in economic, social, and environmental conditions can mitigate the detrimental effects of negative factors. This highlighted the potential for interventions targeting positive factors to offset systemic inefficiencies and challenges in the food system.

The construct of positive factors captured variables that have a significant impact on food security. Among these, GDP had a particularly strong positive contribution, with a coefficient of 0.845, highlighting its critical role in ensuring the availability and accessibility of resources that support food systems. Expenditures on agriculture also contributed positively, with a value of 0.434, indicating that investment in this

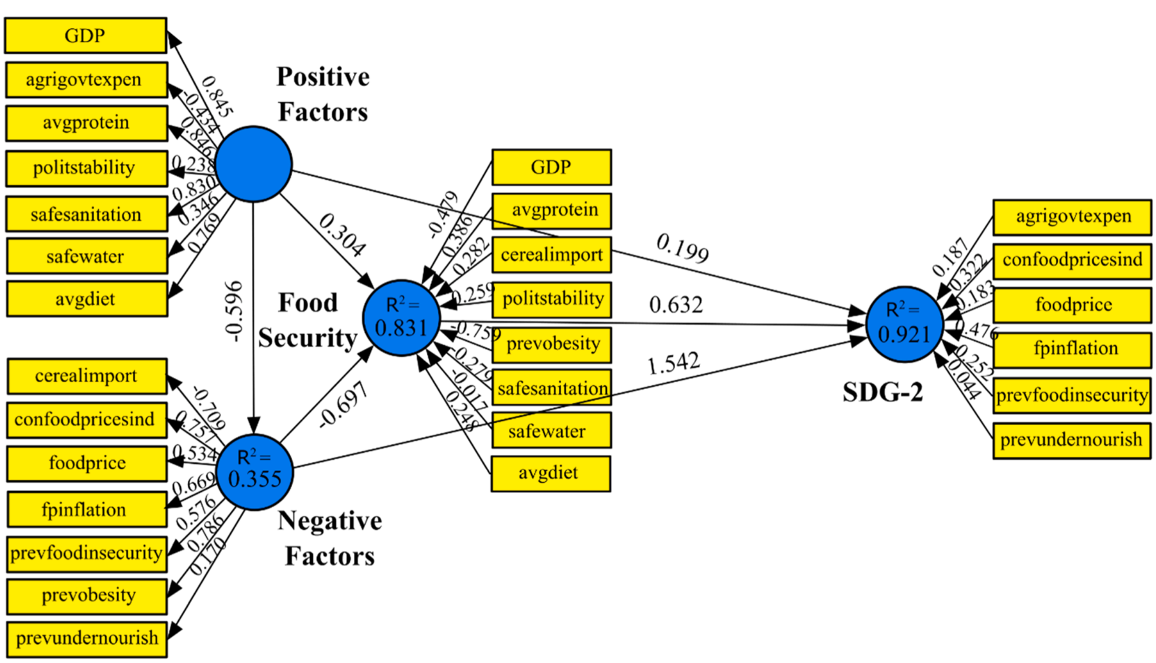

Fig. 5. Structural equation model of positive and negative determinants of food security and their impact on SDG-2 progress.

sector plays a meaningful role in bolstering food security. Average protein supply emerged as another significant variable, with a coefficient of 0.846. This suggested that better protein availability supports outcomes like food security, health, or nutrition. Similarly, access to safe sanitation (0.830) and safe clean water (0.346) were key contributors, emphasizing their foundational role in promoting health and nutrition. The quality of diets, reflected through the average diet indicator, contributed significantly with a coefficient of 0.769. Collectively, these positive factors exerted a strong influence on food security, with an overall impact of 0.304, underscoring their importance in achieving sustainable outcomes. However, positive Factors, such as GDP and access to safe water, exhibited a positive and significant impact on Food Security, with a path coefficient of 0.304 ($p = 0.022$). This trend of the SEM analysis (Fig. 5) supported hypothesis 1. In addition, this underscored the importance of fostering economic growth and improving social and environmental conditions to enhance food security outcomes. Nonetheless, the direct effect of positive factors on SDG-2 was not significant (coefficient = 0.199, $p = 0.462$), suggesting that their influence on SDG-2 might be more indirect, mediated through food security or other pathways.

In contrast, the construct of negative factors included variables that hinder food security. Cereal import dependency had a substantial negative influence, with a coefficient of 0.709, reflecting the vulnerabilities associated with relying on external food sources. The results of the SEM analysis (Fig. 5) supported the second hypothesis (H2). Consumer food prices (0.757), food price anomalies (0.534) and food price inflation (0.669) further exacerbated food insecurity by reducing affordability and creating economic barriers to access. The prevalence of obesity (0.786) underscored inefficiencies in food systems, reflecting imbalances in dietary quality and overconsumption trends that detract from their overall effectiveness. Meanwhile, the prevalence of severe food insecurity (0.576) highlighted systemic challenges, including inequality in food distribution and access, which further compromise the system's ability to deliver equitable and sustainable outcomes. Taken together, these negative factors had a pronounced adverse effect on food security, with a combined impact of −0.697, indicating the urgency of addressing these challenges through targeted interventions. However, negative factors exerted a strong and statistically significant negative impact on Food Security, with a path coefficient of −0.697 ($p = 0.001$). This highlights how adverse conditions, such as food price inflation or severe food insecurity, detracted from achieving food security. Moreover, negative factors demonstrated a significant and strong direct positive relationship with SDG-2 (coefficient = 1.542, $p = 0.001$), possibly capturing systemic inefficiencies that are interconnected with broader challenges in meeting SDG-2 targets.

Furthermore, food security, the central construct in the model, was shaped by the relationship of these positive and negative factors. It was significantly influenced by GDP (0.479), which underscored the importance of economic strength in improving food security outcomes. Average protein supply (0.386), Safe water (0.248) and sanitation (0.017), although smaller in effect, remained critical to health and food security. Importantly, the prevalence of obesity (−0.759) further illustrated systemic inefficiencies. This highlighted the need for comprehensive approaches to food security that address both access and quality. Overall, the combined influence of these factors resulted in a food security construct with a strong positive contribution to SDG-2, evidenced by a coefficient of 0.632.

The direct relationship between food security and SDG-2 had a path coefficient of 0.632 with a p-value of 0.027, suggesting a positive and significant effect at the significance level of 0.05. This indicated that while food security contributes to the achievement of SDG-2, the strength of this contribution was less robust in this model. However, this food security showed a significant positive impact on the achievement of zero hunger, as indicated by the path coefficient of 0.632. Additionally, direct influences such as agricultural expenditures (0.187) further contributed to progress toward SDG-2, reinforcing the importance of targeted investments in sustainable food systems.

This analysis provided critical insights for policymakers and practitioners. Enhancing positive factors like GDP growth, agricultural investment, and access to sanitation and clean water can significantly improve food security outcomes. At the same time, reducing negative factors such as cereal import dependency, food price instability, and inefficiencies in food systems is essential for addressing vulnerabilities. By prioritizing these interventions, significant progresses can be made toward achieving SDG-2 and ensuring sustainable, equitable food systems for all. Overall, the results emphasised the critical role of mitigating negative factors to enhance food security while leveraging positive factors to create a more balanced and sustainable pathway toward achieving SDG-2.

Further to the structural equation model presented in Fig. 5, Fig. 6 delineates the precise mediation pathways through which positive and negative determinants affect food security, ultimately influencing progress toward SDG-2 (Zero Hunger).

Fig. 6 illustrates the mediation analysis, detailing the direct, indirect, and total effects of key determinants on food security and SDG-2 outcomes. This analysis was conducted using Eq. (6), with 95 % confidence intervals (error bars) derived from 5000 bootstrap samples. Effects whose intervals do not cross zero are statistically significant ($p < 0.05$). Notably, the particularly narrow intervals for GDP reflect its consistently robust influence, while wider intervals for variables such as undernourishment prevalence, food insecurity, agricultural expenditure, food prices, the consumer food price index, and food price inflation indicate greater variability in their mediated effects.

For example, concerning the prevalence of undernourishment, GDP's influence is complex. While its total effect was negative (around −0.39), suggesting that economic growth is ultimately beneficial, a small negative indirect effect of GDP (−0.05) was observed. This indicated that the processes of economic growth, while positive overall, might inadvertently trigger shifts in other areas (e.g., agricultural practices, labour markets) that have localized negative consequences for undernourishment. In contrast, cereal imports demonstrated a strong direct effect on reducing undernourishment (−0.5), highlighting the importance of access to diverse food sources. Political stability and safe water access also played crucial roles, with positive indirect (0.22) and direct (0.23) effects, respectively. The prevalence of obesity, while often seen as a separate issue, also exhibited a positive total effect (0.15) on undernourishment, suggesting complex interconnections within the food system. These results of the mediation analysis (Fig. 6) supported hypothesis 2.

Turning to food insecurity, GDP again exhibited a negative indirect effect (−0.19), while its total effect was positive (0.15), further emphasizing the complex role of economic growth. Cereal imports (0.15) and safe sanitation (0.1) showed direct effects in reducing food insecurity. Safe water access also demonstrated a positive total effect (0.22). These results of this examination (Fig. 6) supported hypothesis 3.

For agricultural government expenditure, GDP's indirect effect was negative (−0.1), and its total effect was −0.42, suggesting that economic growth might reduce the need for agricultural subsidies. Average protein supply (−0.3) and cereal imports (−0.59) also had negative direct effects on agricultural expenditure. Political stability (0.22) and obesity prevalence (0.37) had positive total effects, potentially reflecting how these factors influence agricultural investment.

Regarding food price, GDP had a positive direct effect (0.2), contributing to price stability. Average protein supply (0.03) and cereal imports (0.04) also showed positive indirect effects. Obesity prevalence, safe sanitation, and safe water access had positive total effects, highlighting their roles in price stability.

For the consumer food price index, GDP showed a positive direct effect (0.22). Average protein supply (0.01) and average dietary energy (0.02) exhibited direct effects. Obesity prevalence (0.42), safe sanitation, and safe water access again had positive total effects.

Finally, concerning food price inflation, GDP had a positive direct

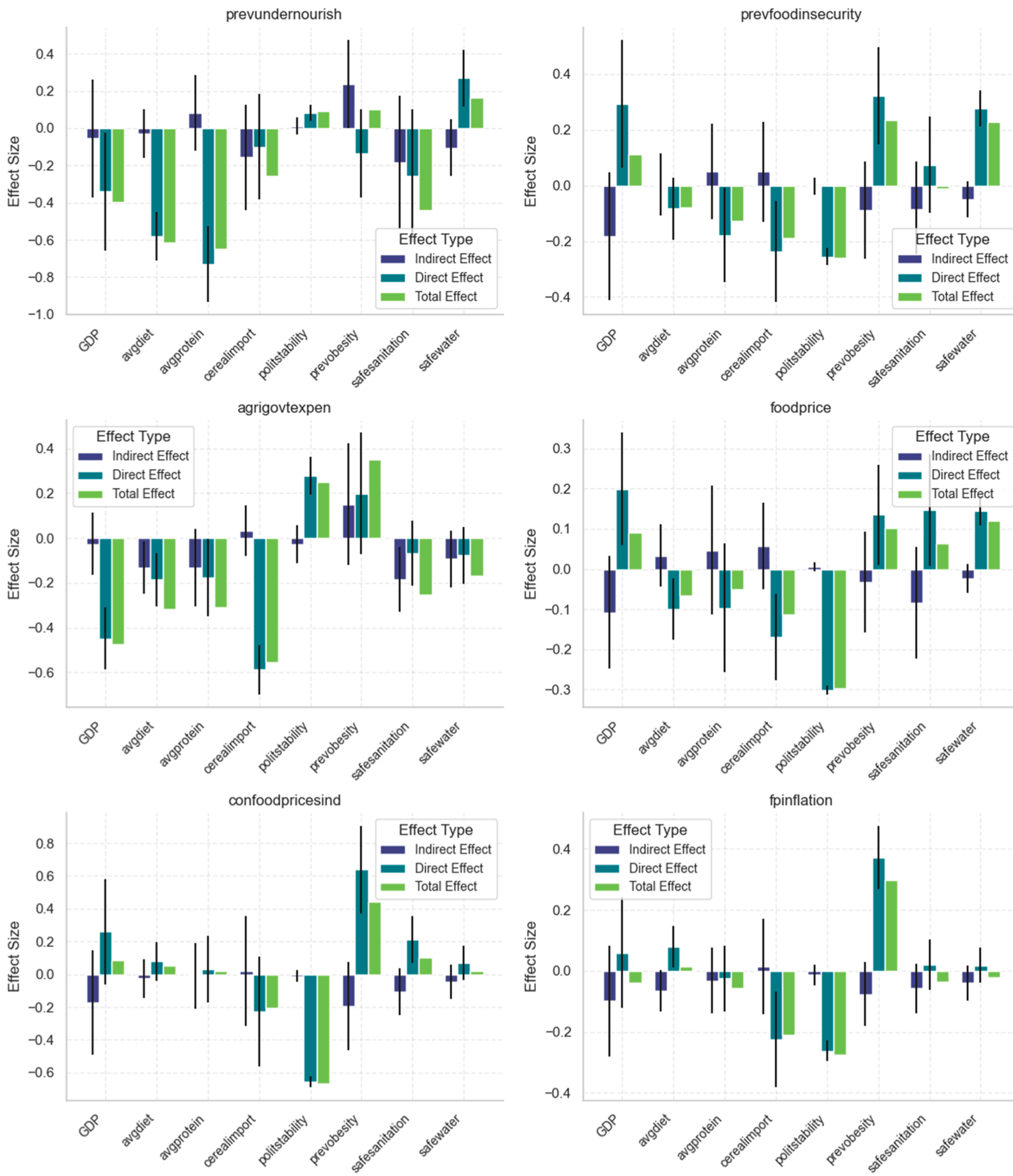

Fig. 6. Mediation pathways extending the SEM framework to SDG-2 outcomes.

effect (0.09). Average dietary energy (0.1) showed a direct effect, while cereal imports had a negative direct effect (−0.21). Obesity prevalence (0.3), safe sanitation (0.01), and safe water access (0.01) had positive direct effects.

These detailed results from the mediation analysis, combined with the broader SEM findings, provided a nuanced understanding of the factors driving food security and progress toward SDG-2. By dissecting the direct and indirect pathways, more targeted and effective interventions can be developed to address this multifaceted challenge.

To further validate the robustness of our SEM findings across different country contexts within the EU, we conducted leave-one-out cross-validation by sequentially excluding each country from the analysis and re-estimating the model. This approach allowed us to determine whether our results were unduly influenced by any single country's

Table 2
Leave-one-out cross-validation results for SEM path coefficients.

Country Excluded	Positive Factors → Food Security	Negative Factors → Food Security	Food Security → SDG-2	Model Fit (CFI)
None (Full Model)	0.304	−0.697	0.632	0.94
Austria	0.298	−0.712	0.641	0.93
Belgium	0.311	−0.689	0.629	0.94
Czech Republic	0.307	−0.701	0.635	0.92
Germany	0.289	−0.708	0.645	0.93
Hungary	0.325	−0.673	0.618	0.95
Netherlands	0.287	−0.715	0.649	0.92
Poland	0.316	−0.685	0.624	0.94
Slovakia	0.332	−0.668	0.612	0.95

specific characteristics. As shown in Table 2, the key path coefficients remained remarkably stable across all iterations, with minimal variations in effect sizes and consistent significance patterns. These results confirm that no single country disproportionately influenced the relationships between positive factors, negative factors, food security, and SDG-2 outcomes, reinforcing the reliability of our conclusions.

Table 2 presents the results of leave-one-out cross-validation analysis (calculated through Eq. (7)), demonstrating the robustness of our SEM model across different country configurations. The consistency of path coefficients when sequentially excluding each country indicates that our findings are not driven by any single country's data. The stability of the relationship between positive factors and food security (ranging from 0.287 to 0.332) and negative factors and food security (ranging from −0.715 to −0.668) across all model specifications confirms the reliability of our core findings. Similarly, the food security to SDG-2 relationship maintains consistent significance across all cross-validation iterations, with coefficients varying minimally between 0.612 and 0.649.

The robust analytical results derived from Figs. 1–6 and Table 2 collectively validate the relationships between positive and negative factors and food security outcomes, highlighting critical patterns and interactions across the selected EU countries. These compelling findings, underpinned by significant SEM path coefficients (Table 2) and clear visual evidence (Figs. 1–6), provide a solid foundation for identifying key drivers of food security and developing actionable policy recommendations to enhance food security and facilitate the achievement of SDG-2. The following policy recommendations are derived from this research:

1. Economic performance significantly influenced food security outcomes across the selected EU countries. Austria and the Netherlands, with GDP growth rates of 5.0 % and 4.8 % respectively between 2010 and 2024, exhibited the highest levels of food security, as reflected in their affordability and stability indicators (Fig. 2). In contrast, Hungary and Slovakia, with slower GDP growth rates of 2.5 % and 2.3 %, faced considerable challenges in food affordability (Fig. 3). The strong positive effect of GDP on food security (SEM path coefficient = 0.845) (Fig. 5; Table 2) reinforces the importance of fostering economic resilience through targeted investments in agriculture, infrastructure, and social programs to mitigate food insecurity.
2. Cereal import dependency significantly influenced national food security, exposing some countries to global market fluctuations. The Netherlands, with a dependency rate of 90.3 %, was particularly vulnerable to disruptions in global food supply chains (Fig. 2). In contrast, Hungary and Poland maintained stronger positions in global trade networks as net cereal exporters with negative import dependence values of −12.5 % and −9.8 %, respectively (Fig. 2; Fig. 3). The strong negative impact of cereal import dependency on food security (SEM path coefficient = −0.709) (Fig. 5; Table 2) underscores the need for diversification in food sourcing strategies, including promoting domestic production capacity and establishing resilient trade agreements to reduce external vulnerabilities.
3. Nutritional imbalances presented a dual challenge in the region, with both overnutrition and undernutrition affecting food security. Obesity rates remained high in Hungary and Slovakia at 25.4 % and 26.1 %, respectively (Fig. 2), while Slovakia recorded the highest undernourishment prevalence at 4.9 %, compared to Germany's relatively low rate of 0.9 % (Fig. 2; Fig. 3). The positive association between obesity and undernourishment (SEM path coefficient = 0.15) (Fig. 6; Table 2) highlights systemic imbalances within food systems that require integrated policies addressing excessive caloric intake alongside nutritional deficiencies through education campaigns, dietary diversification programs, subsidies for healthy foods, and improved healthcare access.
4. Investment in agriculture played a decisive role in food security, influencing both domestic food production and market stability across 8 EU Member States. Czechia led the region with an agricultural government expenditure score of 2.5 (Fig. 2), demonstrating its commitment to bolstering food systems, while Belgium and the Netherlands allocated minimal shares of only 0.3 % and 0.4 %, respectively (Fig. 2). The significant positive impact of agricultural expenditure on food security (SEM path coefficient = 0.434) (Fig. 5; Table 2) highlights the need for sustained public investment in agriculture to build long-term resilience against external shocks while ensuring stable food production.
5. Food price stability remained a critical determinant of food security, as price fluctuations affected affordability for vulnerable populations across selected 8 EU countries (Table 2). Slovakia experienced substantial food price anomalies, with a consumer price index (CPI) deviation of +2.7 % (Fig. 2), making nutritious foods less accessible for low-income households (Fig. 3). In contrast, Austria maintained stable food prices (−1.2 % CPI deviation) (Fig. 2), ensuring predictable costs for consumers across socio-economic groups (Table 2). The strong negative impact of food price inflation on food security outcomes (SEM path coefficient = −0.697) (Fig. 5; Table 2) emphasizes the need for market interventions such as subsidies or price controls to stabilize costs and improve affordability for vulnerable populations.
6. Access to safe water and sanitation directly influenced food security by improving dietary utilization and reducing health risks associated with malnutrition or waterborne diseases (Table 2). Germany achieved near-universal sanitation coverage at 99.8 % of its population (Fig. 2), supporting better nutrition absorption and public health outcomes, whereas Hungary faced persistent challenges with only 75.4 % access to safe water among its population (Fig. 2; Fig. 3). The strong positive impact of safe water access on food security outcomes (SEM path coefficient = 0.346) (Fig. 5; Table 2) underscores the urgency for infrastructural improvements that enhance public health systems while supporting SDG-2 targets.
7. Severe food insecurity remained a pressing concern, particularly in economically constrained countries despite economic growth trends across EU Member States (Table 2). Czechia and Hungary reported the highest proportions of their populations affected by severe food insecurity at up to 1.9 % each (Fig. 2; Fig. 3), highlighting that GDP growth alone does not guarantee equitable access to adequate nutrition across socio-economic groups (Table 2). The significant negative association between severe food insecurity and overall food security outcomes (SEM path coefficient = −0.759) (Fig. 5; Table 2) calls for targeted interventions such as direct assistance programs, social safety nets, community-based initiatives, and inclusive policies aimed at reducing disparities.

These findings highlighted the intricate relationship between economic performance, agricultural policies, food affordability, and nutritional health. Addressing these factors through integrated, country-specific policies is crucial for advancing sustainable food security in the selected eight EU countries and achieving SDG-2.

5. Conclusions

A deeper understanding of the complex connections between factors that promote and impede food security within eight EU Member States has been achieved through this research, proposing vital perspectives for overcoming barriers to the successful implementation of SDG-2. This study highlights GDP growth as a key driver of food security (0.845) while identifying cereal import dependency (−0.709) as a major vulnerability. Targeted interventions can enhance resilience against structural challenges.

In response to our first research question on factor interaction, we found that positive and negative factors create complex feedback loops rather than operating in isolation. The strong negative correlation (−0.596) between positive and negative factors demonstrates how improvements in one domain can mitigate challenges in another (Fig. 5), creating opportunities for strategic policy interventions that maximize beneficial spillover effects.

Addressing our second research question on food security's contribution to SDG-2, our findings confirm that food security serves as a critical mediating mechanism (coefficient=0.632) through which economic and social factors influence SDG-2 outcomes (Fig. 5). The mediation analysis revealed nuanced pathways through which factors like GDP and agricultural investment translate into improved food security and ultimately SDG-2 achievement (Fig. 6), highlighting the importance of systemic approaches that address both immediate food access and long-term sustainability.

Regarding our third research question on mitigation potential, we discovered that positive factors can indeed counterbalance negative influences, but their effectiveness varies significantly across national contexts. Countries with robust positive indicators, such as Austria and The Netherlands with GDP growth rates of 5.0 % and 4.8 % respectively, demonstrated greater resilience against negative pressures (Fig. 2), suggesting that strengthening economic foundations, infrastructure, and governance creates a buffer against food system vulnerabilities.

The geographical patterns highlight diverse food security challenges requiring tailored, context-specific interventions rather than one-size-fits-all approaches. This regional heterogeneity underscores the need for policy frameworks that account for varying national capacities, vulnerabilities, and strengths when designing food security initiatives (Fig. 4).

Sustainable European food security hinges on integrated approaches addressing interconnected challenges: economic disparities, agricultural investment gaps, nutritional imbalances, and infrastructure deficiencies. By amplifying positive catalysts while systematically reducing negative influences, EU nations can strengthen their resilience and advance towards SDG 2′s zero hunger vision.

6. Study limitations and further research directions

While this study provided valuable insights, it had several limitations. First, its focus on a subset of EU countries over a 14-year period may not fully capture the diversity of food security conditions across the entire EU. Second, while the selected variables effectively highlighted key economic and agricultural influences, they excluded important considerations such as climate change, food waste, and social safety nets, all of which play a critical role in shaping food security. Third, cultural and environmental differences that influence national food policies and consumer behaviour have not been fully considered. Fourth, methodologically, SEM identified structural relationships but did not imply causality, limiting the extent to which policy recommendations can be directly inferred. Finally, the results may not be fully generalizable across all EU countries due to differences in economic structures, agricultural policies, and social safety nets.

Future research should take a broader and more integrated approach to address these gaps. Expanding the geographical scope to include additional EU countries and non-EU comparisons could deepen our understanding of regional food security dynamics. Longitudinal studies examining the evolution of food security in response to economic, social, and environmental changes would provide further insights. Qualitative research, incorporating interviews with policymakers, farmers, and consumers, could offer a more nuanced understanding of the complex challenges and opportunities in ensuring food security. Moreover, exploring the role of climate resilience and technological innovation in agriculture would enhance our ability to address emerging threats. By integrating economic, social, and environmental dimensions, future studies can provide stronger policy recommendations to build a more sustainable and resilient food system in Europe.

Ethical approval

This study did not involve any kind of clinical or medical experimentation or any identifiable human material and data. The data for analysis of research was collected from databases.

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CRediT authorship contribution statement

Mohammad Fazle Rabbi: Writing – original draft, Visualization, Software, Data curation, Conceptualization. **Sándor Kovács:** Writing – review & editing, Visualization, Methodology. **József Popp:** Writing – review & editing, Conceptualization. **Veronika Fenyves:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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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Data availability

Data will be made available on request.

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