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Muhammadiyah University of Makassar, Indonesia

*CORRESPONDENCE
Oluwaseun Adeoye Oyebamiji
seun.bamiji.adeoye@gmail.com

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Beyond income: governance and protein supply drive global food security

Oluwaseun Adeoye Oyebamiji* and Berna Türkekul

Department of Agricultural Economics, Faculty of Agriculture, Ege University, Izmir, Türkiye

Introduction: Most global food security assessments rely on subjective expert weights, which limits temporal comparability and risks underestimating governance as a structural determinant. This study aims to address these limitations by developing an objective, data-driven Food Security Index that prioritizes empirical weighting over qualitative assumptions.
Methods: The study applies Principal Component Analysis (PCA) to eight indicators across the four FAO pillars (Availability, Access, Utilization, and Stability) for 122 countries from 2000 to 2021. Weights were derived empirically from the data rather than expert opinion. Furthermore, countries were grouped into four distinct security tiers using K-means clustering, and convergent validity was tested against the Global Food Security Index (GFSI) using Spearman's rank correlation.
Results: The first principal component (PC_1) explains 60.36% of the total variance, identifying political stability and protein supply as the strongest contributors to the index. Sub-Saharan Africa and South Asia are concentrated in low-security tiers regardless of income variation, while several upper-middle-income countries underperform due to inequality and institutional fragility. The index demonstrates strong convergent validity with the GFSI ($\rho = 0.81$).
Discussion: The findings suggest that income alone is neither necessary nor sufficient for food security; governance quality and dietary adequacy (e.g., protein supply) are more significant "anchoring" factors than simple calorie availability. These results carry direct implications for SDG 2, suggesting that achieving "Zero Hunger" requires a shift from income-centric strategies toward governance reforms and targeted nutritional quality investments. Policy priorities should be tiered: focusing on foundational infrastructure in low-security contexts, shock-resilience in middle tiers, and subnational interventions in higher-performing nations where internal deprivation is often masked by national aggregates.

KEYWORDS
dietary intake, Food Security Index, objective weighting, policy interventions, regional disparities

1 Introduction

Nearly one in ten people worldwide experience chronic hunger, yet existing tools to measure and monitor food security often fail to capture its full complexity (FAO, 2022). The challenge is not merely one of data scarcity but of methodology. How do we objectively capture an anomaly as multifaceted as food security when conventional indices rely on subjective expert weightings that may inadvertently privilege certain dimensions over others? This question has become increasingly urgent. Cascading global crises (including the COVID-19 pandemic, the Ukraine conflict, and accelerating climate disruption) expose fundamental weaknesses in national and regional food systems (World Food Programme, 2022; Barrett, 2021).

Food security, as defined by the Food and Agriculture Organization (FAO, 2006), encompasses four interdependent pillars: availability (enough food), access (economic and physical ability to obtain food), utilization (nutritional adequacy and food safety), and stability (consistency across all dimensions over time). Yet most existing measurement frameworks struggle to adequately integrate these dimensions. The widely cited Global Food Security Index (GFSI), for instance, relies on expert-weighted indicators. While valuable for global monitoring, this approach may introduce subjective elements and limit temporal comparability across different methodological iterations (Jones et al., 2021; Tendall et al., 2015). Other studies focus narrowly on calorie availability or single-country contexts, limiting their utility for cross-national policy coordination (Sassi, 2015; Omilola, 2010).

The empirical evidence confirms that governance quality, particularly political stability, control of corruption, and government effectiveness, constitutes a primary driver of food security outcomes, a finding that data driven measurement methods help reveal where subjective indices may obscure such relationships (Anser et al., 2021; Asare-Nuamah et al., 2023). Panel studies across multiple regions demonstrate that improvements in governance are associated with substantial food security gains, with West African countries experiencing increases of roughly 12–20 percent following improvement in government effectiveness and anti-corruption measures (Anser et al., 2021). Cross country evidence spanning 124 countries over three decades further establishes that political stability and democratic accountability significantly improve dietary energy supply, while corruption and conflict systematically undermine it (Abdullah et al., 2020). These governance effects operate through multiple mechanisms: they determine whether food aid translates into nutritional improvements (Cassimon et al., 2023), condition the impact of capital flows on food outcomes (Cassimon et al., 2022), and amplify the benefits of technological adoption such that ICT investments yield greater food security returns where government effectiveness is strong (Anser et al., 2021). Country case studies reinforce this pattern: Brazil's dramatic reduction in food insecurity during 2004 to 2014 coincided with governance frameworks that enabled equitable social policies, while subsequent policy shifts that weakened those protections produced rapid reversals (Pérez-Escamilla et al., 2024). Collectively, this evidence positions governance not as a peripheral consideration but as a foundational determinant that shapes whether food systems deliver availability, access, utilization, and stability across diverse contexts.

The consequences of inadequate measurement extend beyond academic debates. Policymakers allocating scarce resources need to know whether to prioritize agricultural infrastructure, social safety nets, or nutrition interventions. These decisions hinge on understanding which dimensions of food security are most binding in specific contexts. International donors require comparable metrics to identify where assistance will yield the highest returns. Yet without a transparent, data-driven framework that objectively weights indicators according to their empirical contribution, such targeting remains imprecise.

Recent studies increasingly use multivariate methods to address these measurement issues. Principal Component Analysis (PCA) has been effective in regional applications (Assefa, 2015; Omilola, 2010) and in household-level work (Wineman et al., 2017), because it assigns indicator weights from observed variance rather than expert opinion. Yet most PCA applications remain geographically narrow, often restricted to a single region or country. Many rely on cross-sectional designs that cannot capture change over time, and only a few validate their indices against recognized benchmarks or combine PCA with clustering to produce policy-relevant groupings. Recent work, such as Matejková et al. (2024) on EU food security, shows the value of PCA-based measurement, yet its scope remains regional. Our study extends this approach to 122 countries across all income groups and regions over two decades, combining a longitudinal design with K-means-based clustering and systematic external validation. Unlike existing indices that rely on fixed weights, the proposed FSI derives data-driven weights via PCA. Furthermore, classifying countries with K-means clustering offers a new, policy-relevant framework for targeting interventions.

This study addresses these limitations by developing a Food Security Index (FSI) using PCA to derive indicator weights directly from the data rather than expert opinion across 122 countries from 2000 to 2021. Applied to eight rigorously selected indicators spanning all four FAO pillars, the approach ensures that the index reflects actual variation in food security outcomes rather than assumed relationships. We then classify countries into distinct security tiers through cluster analysis, enabling policy-relevant stratification that accounts for both structural vulnerabilities and institutional capacity. Finally, we validate the FSI against the Global Food Security Index to assess convergent validity while examining what additional insights a data-driven approach provides.

Several empirical patterns emerge from this analysis. The study contributes to literature in four ways. First, it introduces a global, time-consistent index built on a transparent and replicable statistical method. The index empirically demonstrates that governance indicators (like political stability) and diet quality (like protein supply) are the primary drivers of food security outcomes. This finding is often obscured in subjective or income-focused indices. Second, it expands the number of countries and years analyzed, offering broader geographic and temporal coverage than most previous studies. Third, existing index's reliance on expert-weighted, income-focused indicators can obscure the critical, independent role of governance and understate the importance of diet quality over mere caloric availability. While some regional studies have used PCA (Assefa, 2015) or clustering (Facendola et al., 2023), no existing study combines (1) a globally comparable, longitudinal PCA-derived index that objectively captures all four FAO pillars, with (2) a cluster-based classification to reveal the distinct food security trajectories shaped by the interaction of governance, protein supply, and income. This study addresses that gap.

The contribution of this study is three fold. Methodologically, it advances food security measurement by replacing subjective weights with empirically derived ones through PCA, while adding cluster-based classification absent from fixed-weight indices. Substantively, it reveals that governance quality and protein adequacy, not merely calorie availability, anchor food security outcomes. These finding shifts policy focus toward institutional resilience and diet quality. Operationally, it provides a scalable, updateable framework that governments can use to benchmark progress, international agencies can apply to target assistance, and researchers can extend to subnational analysis or integrate with climate, health, and poverty data.

The following sections detail our methodology, present results across regional and income dimensions, and discuss implications for tier-specific policy interventions. Section 2 reviews relevant literature on food security measurement and PCA applications. Section 3 describes data sources, indicator selection, and analytical procedures. Section 4 presents principal component loadings, cluster characteristics, and validation results. Section 5 discusses findings in relation to existing evidence and policy frameworks. Section 6 concludes with recommendations for differentiated interventions and future research directions.

2 Literature review

Food security measurement remains a persistent challenge in development economics due to its multidimensional nature. The Food and Agriculture Organization's (FAO, 2006) conceptual framework identifies four interdependent pillars: availability, access, utilization, and stability. While this framework has gained widespread adoption, operationalizing these dimensions into quantitative metrics has produced divergent methodological approaches with varying degrees of validity and policy relevance.

The Global Food Security Index (GFSI), developed by the Economist Intelligence Unit (2022), represents one prominent attempt to quantify food security through expert-weighted aggregation of national-level indicators. However, recent critiques have demonstrated three key limitations of this approach. First, the fixed weighting scheme fails to account for structural changes in food systems over time (Jones et al., 2021). Second, its reliance on qualitative assessments introduces subjectivity that complicates cross-country comparisons (Sinkovics and Holzmüller, 2015). Third, the index's partial coverage of FAO dimensions, particularly utilization metrics, creates measurement gaps (Tendall et al., 2015).

In response to these limitations, researchers have increasingly turned to data-driven methods. PCA has emerged as particularly valuable for food security measurement due to its ability to objectively determine indicator weights through variance decomposition (Uddin et al., 2019). Regional applications demonstrate PCA's flexibility, with Omilola (2010) constructing a Sub-Saharan African index revealing infrastructure's role in food access, while Assefa (2015) developed a 53-country model confirming PCA's capacity to capture FAO's multidimensionality. At the household level, Wineman et al. (2017) demonstrate that income-based and calorie-based welfare measures capture different dimensions, while leaving estimated calorie availability largely unchanged through market compensation.

Despite these advances, significant gaps persist in literature. First, most PCA applications remain geographically limited, with few studies achieving global coverage (Harris et al., 2011). Second, the temporal dimension is often neglected, with cross-sectional designs predominating (Maier et al., 2023). Third, while some studies incorporate clustering techniques (e.g., Facendola et al., 2023), none combine global scope, longitudinal analysis, and cluster-based classification as our study does.

Recent scholarship has increasingly emphasized governance and institutional factors as critical but under-measured determinants of food security (Kemmerling et al., 2022). Cassimon et al. (2023) demonstrates how political stability and policy quality mediate the effectiveness of food security interventions, while Schneider et al. (2025) identifies institutional capacity as the key differentiator in national resilience to food system shocks. These findings suggest that existing indices may systematically underestimate governance's role, a gap our study addresses through inclusion of political stability indicators.

Methodological transparency represents another persistent challenge. Hybrid approaches that combine PCA with expert judgment, such as Yuting and Meng's (2024) composite index, introduce subjectivity that can reduce reproducibility unless expert decisions are transparently documented and consistently applied. Conversely, narrowly focused indices (e.g., Akombi et al., 2017 on child nutrition) lack the comprehensive FAO alignment that policymakers require (Singh et al., 2021). Our study advances the field by employing a fully PCA-driven approach across all four FAO dimensions while maintaining strict statistical criteria for indicator inclusion.

The current study contributes to this evolving literature in three keyways. First, we apply PCA to the most comprehensive global dataset to date, covering 122 countries over 21 years. Second, we introduce cluster analysis to enable policy-relevant classification of food security trajectories. Third, we rigorously test our index's validity against established benchmarks while acknowledging residual variance that points to important areas for future research, particularly informal food systems and cultural factors.

3 Materials and methods

3.1 Data source

This study constructs a Food Security Index (FSI) using data from 122 countries spanning 2000–2021. All data were sourced primarily from FAOSTAT. The dataset uses 3-year moving averages, consistent with FAO food security suite reporting standards, which reduces short-term fluctuations and captures medium-term trends. Approximately 5% of observations contained missing values, which were addressed through linear interpolation to maintain temporal continuity within country series.

3.2 Variable selection and screening

We began with 15 candidate indicators representing the four FAO-defined dimensions of food security: availability, access, utilization, and stability (FAO, 2006). To ensure statistical robustness and discriminatory power, we applied a systematic screening process that systematically excluded 7 variables.

3.2.1 Step 1: correlation-based screening

Variables with inter-indicator correlations below 0.3 were excluded, following Field (2009). This removed:

- Cereal import dependency ratio (cerea_impdep)

- Percentage of arable land equipped for irrigation (per_irrigation)
- Value of food imports over total merchandise exports (V_fd_imp_merc_exp)

3.2.2 Step 2: variance assessment

Indicators with low variance across countries and years were excluded due to limited discriminatory power:

- Food price volatility (Food_vol)
- Per capita food supply variability (fsupp_var)

3.2.3 Step 3: conceptual redundancy

Variables that overlapped substantively with retained indicators were excluded:

- Gross per capita food production index (Gross_per capita Food_Prod_Index)—redundant with per capita food production variability
- Food value moving average (Food_val_Mov_Av)—overlapping with production and supply indicators

3.2.4 Step 4: sampling adequacy (MSA)

We calculated the Measure of Sampling Adequacy (MSA) for each remaining variable using the Kaiser-Meyer-Olkin (KMO) test. Only variables contributing to an overall KMO $\geq$ 0.7 were retained, ensuring factorability. The overall KMO score exceeded 0.7, confirming sampling adequacy for the final variable set.

3.2.5 Final variable set

Eight indicators were retained, spanning all four FAO dimensions (see Table 1). These variables are:

1. Average protein supply (Av_protein_sup)
2. Average dietary supply adequacy (Av_diet_supply)
3. Prevalence of undernourishment (p_undernourish)
4. Political stability and absence of violence (Po_Stab)
5. Per capita food production variability (percap_fdprodvar)
6. Prevalence of obesity (Prev_obst)
7. Prevalence of anemia among pregnant women (prev_anem)
8. Depth of the food deficit (Food_def_per_cap)

These variables demonstrated adequate correlation structure, meaningful variance, and strong sampling adequacy for PCA.

3.3 Standardization formula

All indicators were transformed into a normalized scale using the formular:

$$Z_m = \frac{\mu - x_m}{\sigma} \tag{1}$$

where: In equation 1, Z_m is the m indicator's z-score with a mean of 0 and a standard deviation of 1, μ is the mean of the population (the observation), x_m is the m indicator's mean, and σ is the standard deviation of the population.

3.4 PCA specification and index construction

PCA was applied to the eight standardized indicators to objectively derive index weights based on the underlying data structure, avoiding arbitrary weight assignment.

The Kaiser-Meyer-Olkin (KMO) measure was used to test sampling adequacy.

$$KMO = \frac{\sum m \neq k \, r_{mk}^2}{\sum m \neq k \, r_{mk}^2 \sum m \neq k \, p_{mk}^2} \tag{2}$$

$$MSA_m = \frac{\sum m \neq k \, r_{mk}^2}{\sum m \neq k \, r_{mk}^2 \sum m \neq k \, p_{mk}^2} \tag{3}$$

In equations 2 and 3, where: KMO is the overall sample adequacy, MSA_m is the individual variable sample adequacy, r_{mk}^2 is the simple (zero-order) correlation coefficient between variables j and k, and p_{mk}^2 is the partial correlation coefficient between variables j and k, controlling for all other variables. Indicators that did not meet statistical adequacy or showed very low variability across countries and years were excluded. Only indicators contributing to a KMO score above 0.7 were retained, leading to the stepwise removal of 7 variables (Food price volatility (food_vol), Per capita food supply variability (fsupp_var), Cereal import dependency ratio (cerea_impdep), Per capita food supply variability (fd_sup_var), Percentage of arable land equipped for irrigation (per_irrigation), Gross Per Capital Food Production Index, Food Value (smoothed food production value, prices, and expenditures).

PCA was applied to reduce dimensionality and extract principal components. PCA allows the structure of the data to determine the weights assigned to each indicator, removing subjectivity in index construction. It takes the form:

$$FSI_i = a_1 I_{1n} + a_2 I_{2n} + a_3 I_{3n} + \ldots + a_n I_{mn} \tag{4}$$

where:

In equation 4, FSI_i, represents a linear combination of factors or variables. In this research, FSI_i, stands for food security, I_{mn}, represents variables (indicators) from 1 to m for Factor i, where I stands for factor loadings and n stands for countries, and a_n: refers to factor loadings.

To build a reliable food security index, adjustments based on correlation was the primary approach (indicators with less than 0.3 correlation were not retained). As a result, the first component was retained based on eigenvalues greater than one and cumulative

TABLE 1 Eight food security indicators included in the study.

Variable	Codes	Unit	Coverage (3-year average)	Measures
Average protein supply	Av_protein_sup	grams/capita/day	2000–2022	Daily protein availability from all food sources per person.
Average dietary supply adequacy	Av_diet_supply	% of dietary energy needs	2000–2022	Ratio of dietary energy supply to national average requirements.
Prevalence of undernourishment	p_undernourish	% of population	2000–2022	Share of population consuming insufficient calories for an active life.
Political stability and absence of violence	Po_Stab	Index (typically −2.5 to 2.5)	2000–2022	Governance quality affecting food systems (higher = more stable).
Per capita food production variability	percap_fdprodvar	USD/capita (standard dev.)	2000–2022	Volatility in net food production value (constant 2004-2006 USD).
Prevalence of obesity	Prev_obst	% of population (adults)	2000–2022	Share of adults with BMI ≥ 30.
Prevalence of anemia among pregnant women	prev_anem	% of pregnant women	2000–2022	Share of pregnant women with hemoglobin below WHO thresholds.
Depth of the food deficit	Food_def_per_cap	kcal/capita/day	2000–2022	Average daily calorie gap to lift all undernourished to minimum requirements.

variance explained. This first component accounted for 60.36% of total variance of food security.

The final index was constructed as a weighted value of the retained first principal component in line with Assefa (2015). Each country-year pair received an index score reflecting its performance across the eight indicators which represents all four dimensions. Higher scores represent stronger food security outcomes. The approach ensures comparability across countries and over time without relying on arbitrary weights.

To better interpret the index and group countries with similar profiles, K-means clustering was applied. The number of clusters was determined using the Silhouette Score, which measures how well each observation fits within its cluster. A four-cluster solution provided the clearest segmentation. These clusters represent different levels of food security, from low to high.

3.5 Clustering specifications

To facilitate interpretation and identify countries with similar food security profiles, we applied K-means clustering to the PCA-derived FSI scores. The optimal number of clusters was determined using the Silhouette Score, which measures within-cluster cohesion relative to between-cluster separation.

A four-cluster solution maximizes interpretability and statistical fit, segmenting countries into distinct food security categories ranging from low to high performance. Clustering PCA scores (rather than raw index values) preserves the dimensional structure identified during component extraction.

3.6 Validation and robustness

3.6.1 Sensitivity to component selection

To assess whether retaining only PC1 was appropriate, we constructed an alternative index using the first two principal components (jointly explaining 73.05% of variance). Country rankings from the two-component solution showed very high agreement with the single-component solution (Spearman's $\rho > 0.95$), confirming that PC1 captures the dominant food security dimension.

3.6.2 Cross-validation

Following Field (2009), we randomly split the dataset into two halves, performed PCA independently on each subset, and compared factor loadings and explained variance against the full-sample model. Results demonstrated high consistency across splits, supporting the stability of the component structure.

3.6.3 External validation

We compared country rankings from our FSI with The Economist's Global Food Security Index (GFSI) using Spearman rank correlation:

$$rho = \left(1 - \frac{6\sum di^2}{n(n^{2-1)}}\right) \tag{5}$$

In equation 5, rho is the Spearman rank correlation, *di* measures the difference between GSFI and FSI, and n is the number of observations.

This methodology avoids assigning fixed weights to indicators or dimensions. Instead, let the data define the structure of the index. The inclusion of multiple indicators per dimension ensures that food security is measured as a complex and dynamic phenomenon. The use of clustering adds value by enabling cross-sectional interpretation in addition to temporal tracking.

The index can be updated regularly and adapted to include new indicators or additional countries as data become available. The combination of PCA and clustering offers a scalable framework for national and international monitoring. It provides

TABLE 2 The factor explained variance.

Total variance explained						
Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	4.829	60.362	60.362	4.829	60.362	60.362
2	1.015	12.685	73.047	1.015	12.685	73.047
3	0.758	9.475	82.521			
4	0.561	7.009	89.530			
5	0.360	4.502	94.032			
6	0.270	3.378	97.410			
7	0.147	1.838	99.248			
8	0.060	0.752	100.000			

stakeholders with a consistent tool to benchmark performance, design interventions, and track progress. The high correlation between FSI and GFSI rankings confirmed external validity.

3.7 Software and visualization

All data processing, PCA, clustering, and validation analyses were conducted using R Core Team (2022) and Python Software Foundation (2021). Visualizations of temporal trends, cluster distributions, and component loadings were produced using Wickham (2016) and Hunter (2007).

4 Results

4.1 PCA analysis and index construction

The PCA applied in this study used eight selected indicators that met the threshold of sampling adequacy and inter-correlation required for dimensionality reduction. These indicators represent the four pillars of food security: availability, access, utilization, and stability. As reported in Table 2, the first principal component (PC1) explained 60.36% of the total variance and was adopted as the Food Security Index (FSI). This level of variance explained is high in comparison to similar studies (Adjimoti and Kwadzo, 2018; Assefa, 2015; Thomas et al., 2017) and reflects the robustness of the selected indicators and the comprehensiveness of the data structure. Supplementary analysis examined temporal stability of component loadings by splitting the dataset into two periods (2000–2010 and 2011–2021), offering sensitivity analysis to support the approach. Factor loading differences remained below 0.08 for all variables, suggesting the index structure is stable across different time windows.

The variables with the highest positive factor loadings were average protein supply (0.92) and dietary supply adequacy (0.89), both representing the availability dimension. Political stability (0.61) and variability in food production (0.66) also contributed positively. On the other hand, depth of food deficit (−0.89) and malnutrition prevalence (−0.87) had strong negative loadings, capturing aspects of chronic deprivation and poor utilization. This structure supports the multidimensional design of the index and confirms that both supply-side and structural vulnerability indicators are critical in shaping food security outcomes.

TABLE 3 KMO sampling adequacy test.

KMO and Bartlett's test		
Kaiser-Meyer-Olkin measure of sampling adequacy		0.873
Bartlett's test of sphericity	Approx. Chi-square	15785.200
	df	36
	Sig.	0.000

Taken together, the loading pattern reveals two key findings. First, institutional conditions (notably political stability) and diet adequacy (proxied by protein availability) jointly underpin food security outcomes. Second, chronic deficits and undernutrition align in the opposite direction. This empirical structure therefore supports a dual policy orientation that couples investments in resilient supply chains with targeted nutrition measures.

Table 3 presents the KMO measure of 0.873 and significant Bartlett's Test results confirming that PCA is statistically suitable for the sample. The standardization of variables ensures that indicators with large ranges do not dominate the results. Eight indicators with communalities above 0.5 were retained to construct the index.

As depicted in Figure 1, the comparison between our Food Security Index (FSI) and the Global Food Security Index (GFSI) reveals a strong positive correlation (Spearman's $\rho = 0.8086$, $p < 0.0001$). This statistically significant relationship indicates high convergent validity.

This robust association suggests that our index, derived from key indicators such as protein supply, dietary adequacy, undernourishment, and political stability, closely aligns with the globally recognized GFSI benchmark. Besides, the sensitivity results in Table 4 reveal near-identical factor loadings from the splitting of our dataset into random halves for cross validation rounds (e.g., $\Delta \leq 0.021$ for all variables) further demonstrate the stability and reliability of our index. With the first two principal components explaining 73.05% of the variance and a high KMO score (0.873), the FSI provides a consistent and comprehensive measure of food

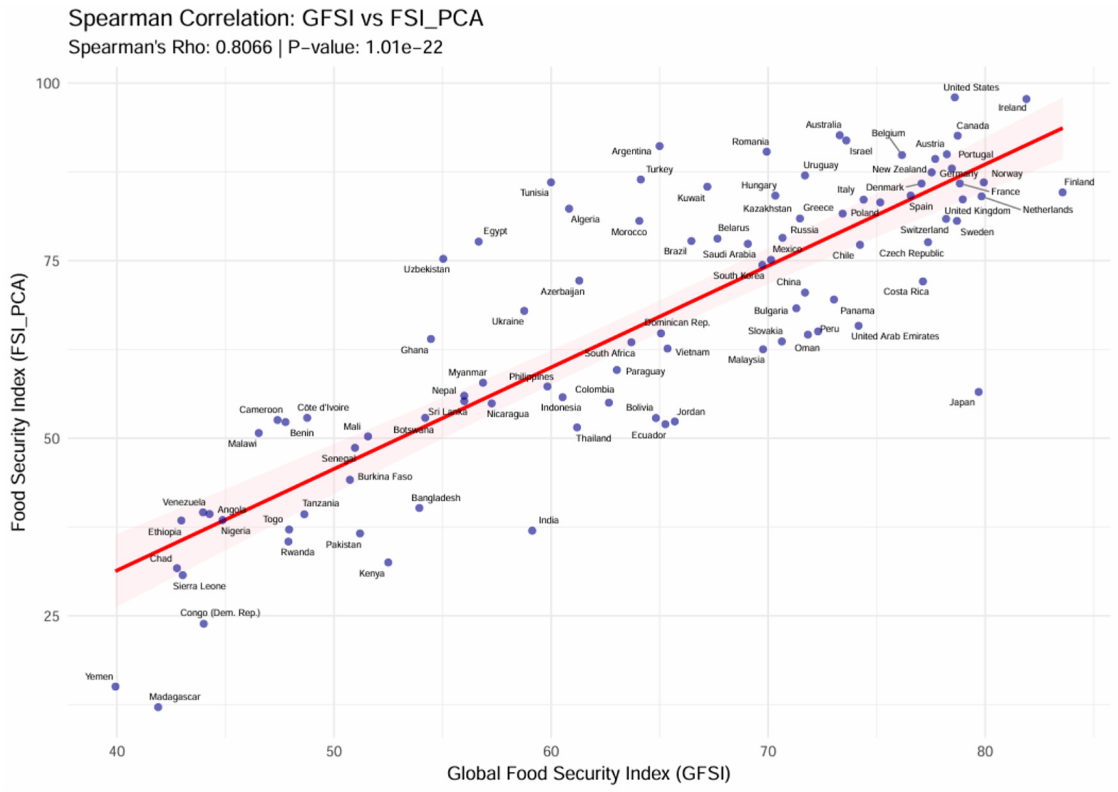

FIGURE 1
Comparison of the study's FSI with GSFI.

security, making it a credible alternative or complementary tool to the GFSI for policymakers and researchers. The significant *p*-value reveals that this correlation is not due to chance, reinforcing confidence in the index's external validity.

4.2 Country classification and clustering analysis

Using PC1 scores, 122 countries were classified into four food security categories: very low, low, moderate, and high. This classification was conducted via k-mean cluster analysis and validated by an average Silhouette Score of 0.555. Table 5 summarizes the thresholds.

Approximately 15.7% of observations were classified as having very low food security, while 32% of observations belonged to the high food security group. This gradient allows both researchers and policymakers to monitor progress and vulnerability across time and space. The four-tier typology is not merely a statistical construct; it aligns with distinct policy needs across country contexts. Nations in the very low and low clusters typically face binding governance and infrastructure constraints that limit the effectiveness of production and market interventions. Countries in the moderate cluster are more exposed to volatility and encounter access bottlenecks, indicating priorities such as risk management, logistics improvements, and price-stabilization tools. High-security countries, while performing well on average, still need to address persistent subnational nutrition gaps through targeted programs and monitoring.

Convergent validity of the constructed FSI was confirmed through a high and statistically significant Spearman correlation with the Global Food Security Index (GFSI) ($\rho = 0.8086$, $p < 0.0001$). The index also demonstrated high internal consistency, with cross-validation using split samples showing minimal variation in factor loadings ($\Delta \leq 0.021$ across all indicators), indicating stable underlying constructs and affirming both the suitability of the PCA method and the relevance of the selected indicators across diverse contexts. Cluster means ranged from -1.63 for the very low group to 1.09 for the high group.

4.3 Regional and income-based patterns

Mobility analysis reveals that movement between clusters is more common in the middle tires. Transitions from Very Low to Moderate or High Food Security are rare, with most upward movement occurring between Low and Moderate clusters. Regional patterns are heterogeneous. From Figure 2, Africa's performance is the most vulnerable globally. Most African countries fall into the Very Low and Low Food Security categories. Over time, improvements have been modest, with only a few countries shifting into Moderate or High Food Security clusters. Most African countries in the Very Low Food Security group are Low-income or Lower-middle-income economies. These countries face recurring

TABLE 4 Cross validation of PCA estimation.

No	Variables	Loading 1	Loading 2	Δ (Difference)
1	Average protein supply	0.4194	0.4165	0.0029
2	Average dietary supply adequacy	0.4146	0.4114	0.0032
3	Prevalence of undernourishment	−0.3756	−0.3725	−0.0031
4	Political stability and absence of violence	0.2924	0.3136	−0.0212
5	Per capita food production variability	0.2077	0.2049	0.0028
6	Prevalence of Obesity	−0.3291	−0.3289	0.0002
7	Prevalence of anemia among pregnant women	−0.3641	−0.3584	−0.0057
8	Depth of the food deficit	−0.3764	−0.3761	−0.0003

TABLE 5 Cluster categorization of FSI score.

Cluster	Label	Average score
1	Very low food security	−1.63
2	Low food security	−0.63
3	Moderate food security	0.29
4	High food security	1.09

shocks, climate, conflict, and inflation, which limit sustained gains in food access and availability. Out of 660 observations, 37% fall under "very low food security" and 44.4% under "low food security." Only Tunisia consistently ranks in the high food security group. Egypt, Morocco, South Africa, and Mauritius occasionally reach medium or high scores.

European countries cluster heavily (see Figure 2) around the High Food Security clusters, with very few observations in the moderate or low food security levels. These countries are overwhelmingly high-income, and this is reflected in their stable food systems, efficient distribution, and low food price volatility. Transitions in European countries generally maintain their position across time periods. In Europe, most countries are placed in moderate or high food security groups. Yet income inequality and economic shocks still affect access for vulnerable populations.

Asia shows more diversity (see Figure 2). A significant share of countries has transitioned from low to moderate food security levels. This progress is more visible among middle-high-income countries like China and Malaysia. Low-income and lower-middle-income countries like Afghanistan or Bangladesh remain in the low category, though some have shown movement over time. Income levels play a clear role in clustering, higher-income countries tend to be more in the high food security cluster. FSI scores in Asia vary widely. Afghanistan, Pakistan, and Yemen remain in the lowest category across the period. This vulnerability was starkly accentuated during the earlier days of the Ukraine war, when import dependencies and institutional collapse led to a near-total breakdown of food systems (UNOCHA, 2022). In contrast, Türkiye, Israel, and Kuwait exhibit high and stable FSI values.

North America is concentrated on the high food security cluster. These countries are all high-income and have robust infrastructures supporting food availability and access. There is little movement between food security levels over time, indicating a steady and secure food environment. South America displays a relatively balanced distribution across the moderate and high food security levels. Some countries like Venezuela experience setbacks, while others like Chile and Uruguay maintain strong food security. Income group distribution suggests a mix of upper-middle and high-income economies, with moderate volatility in their food security status across years. North America demonstrates high food security with stable scores. This region is diverse. Countries range from very low to high food security. Transitions over time show some upward movement, especially in upper-middle-income countries (see Figure 3). But small island developing states (SIDS) often struggle with persistent food insecurity. Their income levels range from lower-middle to upper-middle, and their food security is sensitive to both global markets and environmental shocks.

Figure 2 shows that for Oceania: Australia and New Zealand consistently fall under high food security, while Pacific Island nations like Papua New Guinea have missing values so severe that it was impossible to include them in this study. Hence our study only has Australia and New Zealand. Both countries rank in the high food security group. Australia demonstrates slightly more stable performance. This is attributed to effective agricultural policy, welfare systems, and trade stability.

Looking at income groups, Figure 3 reveals what was expected, however still important. Low-income countries dominate the very low food security category. No country in this group appears in the high food security cluster. Lower-middle-income countries appear in both low and moderate categories, with some upward movement over time. Upper-middle-income countries are more evenly distributed, and several have concentrated on the high food security cluster. High-income countries are almost exclusively in the high food security cluster.

Movement between states is more common in the middle clusters. Transitions from very low to moderate or high food security are rare. Most changes happen between low and moderate, indicating that improving food security requires more than economic growth. Political stability, public spending on nutrition, and resilience to shocks also matter. Food insecurity is heavily concentrated in low-income groups. Almost no presence in the high food security group. These countries lack the resources and infrastructure to make meaningful gains. Low and moderate food security clusters are paramount in the low-middle income groups. Some upward transitions are visible, especially in Asia and South America. Figure 3 shows a clear relationship between national

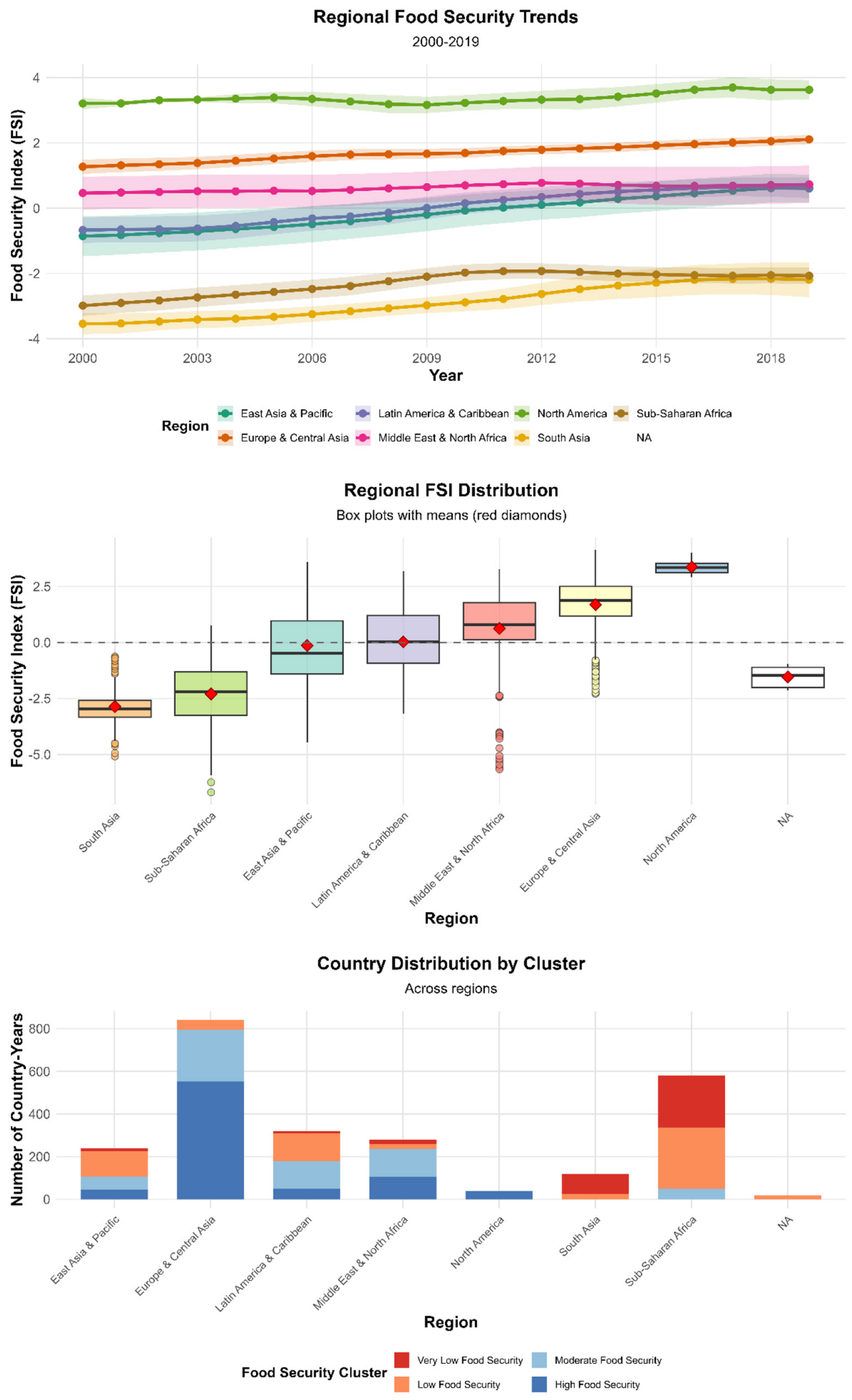

FIGURE 2
Regional decomposition of FSI.

income and FSI score. Low- and low-middle-income countries face extensive food insecurity. High food expenditures as a share of income and dependency on imports, such as wheat from Russia and Ukraine, increase vulnerability.

Figure 4 offers an efficient visualization that summarizes how food security varies across regions, spotlighting which areas need policy attention. Africa, Asia, Central America and the Caribbean are prime food insecurity vulnerability hotspots.

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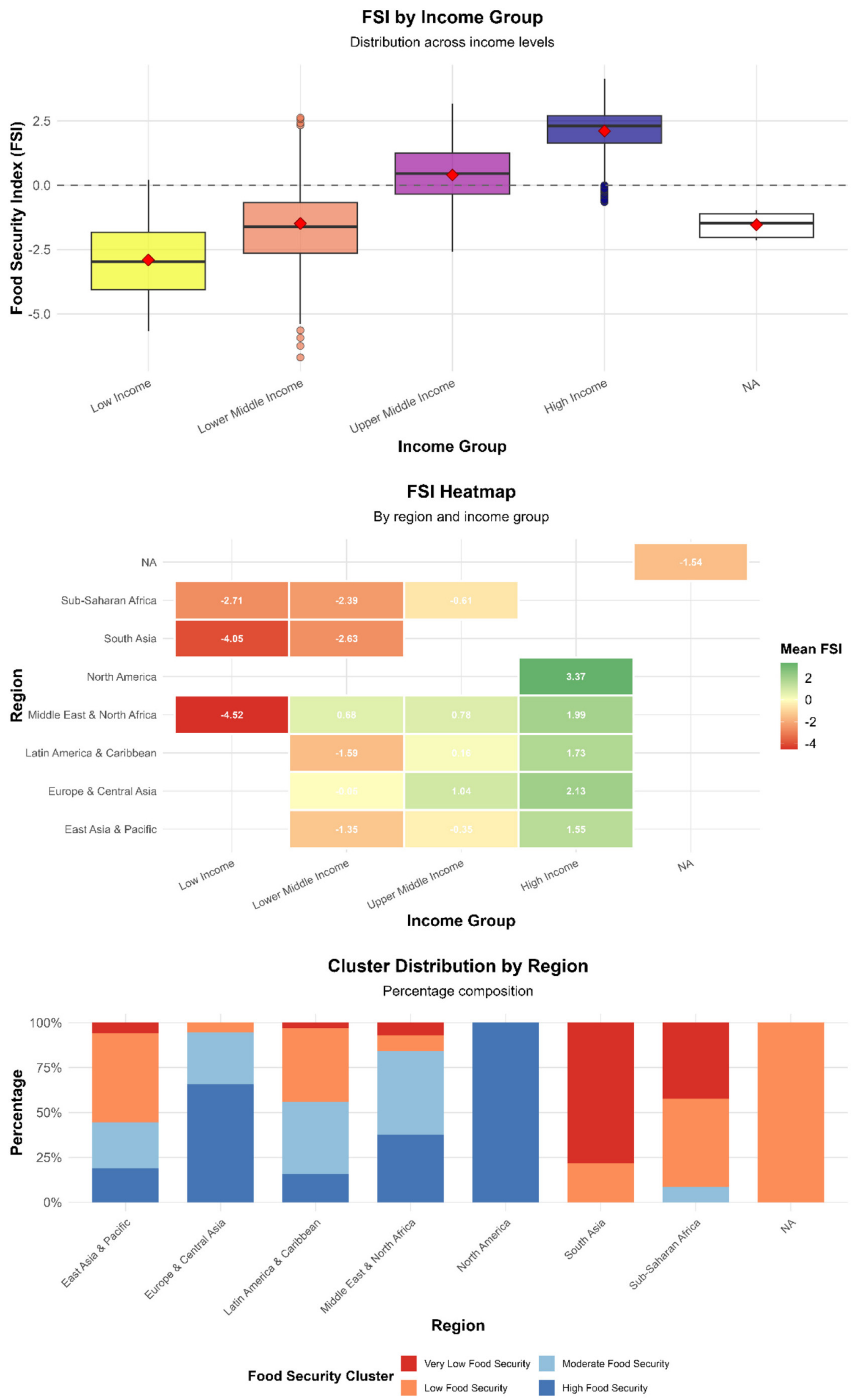

FIGURE 3
Income decomposition by region and FSI score.

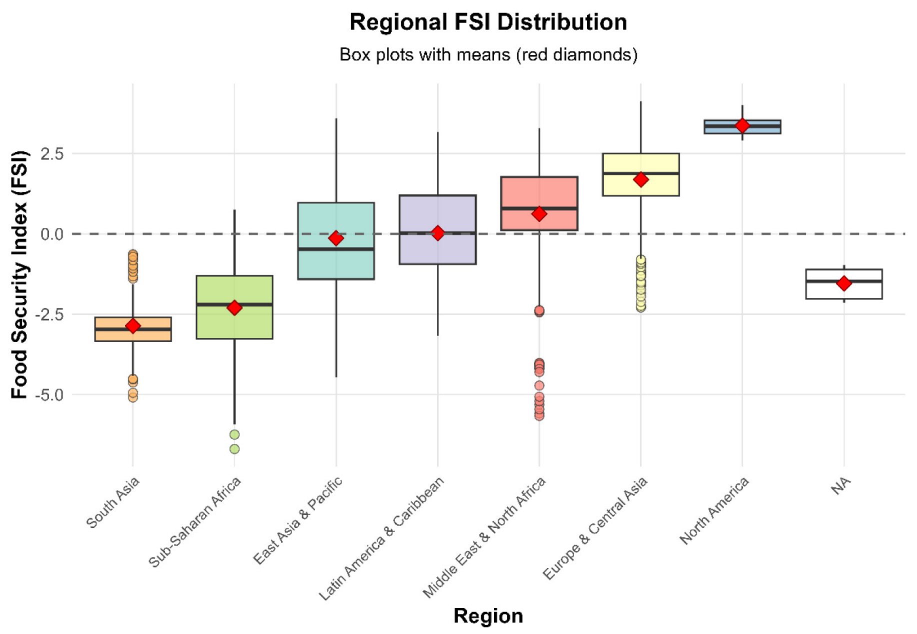

FIGURE 4
Food security regional variation via box-plot.

5 Discussion

5.1 Interpretation of principal component structure

The PCA results reveal that the first principal component (PC1) explains 60.36% of total variance in food security across 122 countries from 2000 to 2021. This finding aligns with established composite index studies that typically report explained variance between 50 and 70% for single-component solutions (Assefa, 2015; Adjimoti and Kwadzo, 2018; Thomas et al., 2017). The dominance of PC1 suggests that food security operates primarily as a unidimensional phenomenon at the macro level, despite its conceptual division into four FAO pillars (availability, access, utilization, stability).

The factor loadings provide insight into which indicators most strongly define this underlying dimension. Average protein supply (loading = 0.92) and dietary supply adequacy (loading = 0.89) exhibit the highest loadings, indicating that nutritional quality, not merely caloric quantity, anchors the food security construct measured by this index. Empirically, the cross-country range in protein supply spans from 29,9 g/capita/day for Democratic Republic of the Congo, in 2022 to 151g/capita/day for Iceland, in the same year, a 5-fold difference (FAO, 2023). This pattern demonstrates protein's superior discriminatory power in differentiating food security levels. The empirical structure is consistent with recent nutritional science emphasizing protein quality and dietary diversity as critical determinants of health outcomes (Coles et al., 2016; Wu et al., 2014).

Political stability demonstrates a moderately high positive loading (0.61) on PC1, positioning it among the more influential structural variables. While this loading does not establish causality, it suggests that institutional resilience correlates strongly with food security outcomes in cross-national data. This pattern aligns with prior research documenting associations between governance quality and nutritional outcomes (Kaufmann et al., 2002; De Janvry and Sadoulet, 2009; Abdullah et al., 2020).

The positive loading for per capita food production variability (0.66) is noteworthy because it represents systemic volatility, a stability dimension indicator. This suggests that countries experiencing greater production fluctuations tend to score differently on the overall food security continuum, reflecting either adaptive capacity differences or vulnerability to shocks.

Conversely, undernourishment prevalence and depth of food deficit show strong negative loadings, as expected. These outcome indicators capture chronic deprivation and represent the inverse of food security, confirming that the index appropriately captures both determinants and consequences of food insecurity.

5.2 Clustering patterns and regional disparities

The K-means clustering analysis, which segmented 122 countries into four distinct food security tiers, reveals substantial regional heterogeneity. Most African countries cluster in the "very low" and "low" food security categories, consistent with documented challenges including conflict exposure, institutional fragility, and agricultural productivity constraints (Bjornlund et al., 2022). For example, chronic instability in South Sudan has been identified as a core contributor to persistent food insecurity (UNICEF, 2021).

North American and European countries consistently appear in the highest food security clusters. This pattern corresponds with the presence of robust public institutions, comprehensive welfare systems, and stable agricultural production systems (Bloem and Farris, 2022; FAO, 2021a). These regional disparities suggest that even where food availability is adequate, structural governance and institutional capacity remain critical differentiators.

Latin American outcomes exhibit significant heterogeneity within the clustering solution. Several upper-middle-income countries, including Venezuela, Brazil, and South Africa, fall into "low" FSI clusters despite their income levels. These findings challenge simplistic assumptions that national income alone determines food security outcomes. These cases likely reflect systemic inequality, institutional weaknesses, and gaps in social safety net coverage (FAO, 2021b), though our methodology does not isolate these specific mechanisms.

Conversely, some lower-income countries such as Rwanda and Vietnam appear in relatively better-performing clusters than their income levels might predict. Vietnam's position aligns with external evidence documenting public investment in rural infrastructure and decentralized governance (Headey et al., 2018), though our analysis does not test these factors directly. Vietnam's trajectory is supported by decentralized governance that allowed for flexible, local responses to food system challenges (Headey et al., 2018). These patterns suggest that governance quality and policy effectiveness may moderate the income-food security relationship, particularly when economic growth is uneven or exclusionary (Rodrik, 2008; Fukuyama, 2013).

Our clustering results challenge the deterministic view of income, revealing significant heterogeneity within income groups (refer to Figure 3). This heterogeneity can be partly explained by the strong loading of political stability (0.61) on PC1. High-income countries almost universally exhibit high governance scores, creating an enabling environment for food security. However, the cases of upper-middle-income countries like Venezuela and South Africa, which fall into lower security clusters, illustrate how governance deficits and systemic inequality can negate the advantages of higher national income. Conversely, the upward mobility of lower-income countries like Vietnam and Rwanda, as noted in our cluster analysis, aligns with external evidence of sustained investments in rural infrastructure, decentralized governance, and pro-poor policies (Headey et al., 2018). These cases suggest that good governance can act as a substitute for high income, enabling more effective translation of available resources into food security outcomes. Thus, while income provides the resources for food security, governance provides the mechanism for their effective and equitable distribution, a distinction with profound policy implications.

5.3 Food security dynamics during global shocks

Recent global disruptions provide natural experiments for observing food security resilience. During the COVID-19 pandemic (2020–2021), countries with higher governance scores, such as Vietnam, recorded comparatively smaller changes in FSI rankings. While our cluster analysis captures Vietnam's upward mobility during this period, our model does not isolate the effects of specific interventions. These patterns suggest a possible association between governance strength and shock absorption capacity, though this relationship warrants further empirical investigation using causal inference methods.

The World Bank's June 2025 LAC Economic Review links regional food security setbacks to rising inflation and slowing economic growth (World Bank, 2025). Although these macroeconomic factors are not directly included in our PCA, they plausibly intersect with the FSI's stability and access dimensions. Countries with high import dependence and weak governance structures, such as Yemen, fell into the lowest security clusters following the Ukraine war disruptions, aligning with existing literature on vulnerability during geopolitical shocks (Acemoglu et al., 2015).

The variability in food production indicator (loading: 0.66) supports the interpretation that structural volatility exacerbates food insecurity outcomes, particularly in fragile contexts. This suggests that countries lacking mechanisms to smooth production shocks face compounded vulnerabilities during global disruptions.

5.4 Validation and external consistency

Our Food Security Index demonstrates strong convergent validity with The Economist's Global Food Security Index (GFSI), as evidenced by a Spearman rank correlation of $\rho = 0.81$ ($p < 0.001$). This high correlation indicates that despite methodological differences, our PCA-derived weights vs. GFSI's expert-assigned weights, both indices capture similar underlying food security dimensions. The comparison with Matejková et al. (2024), who reported $\rho = 0.84$ between their European FSI and GFSI, suggests our results fall within expected ranges for food security index validation.

The explained variance of 60.36% on PC1 aligns with performance ranges reported in comparable studies (Assefa, 2015; Adjimoti and Kwadzo, 2018; Thomas et al., 2017). However, approximately 40% of variance remains unexplained by our model. This residual likely reflects phenomena our eight indicators cannot capture: informal food systems, intra-household allocation dynamics, cultural dietary preferences, food waste patterns, and localized distribution inefficiencies. These unmeasured dimensions represent inherent limitations of macro-level indices constructed from nationally aggregated data.

Sensitivity analysis using the first two principal components (jointly explaining 73.05% of variance) yielded country rankings highly consistent with the single-component solution (Spearman's $\rho > 0.95$). This robustness check confirms that PC1 captures the dominant food security dimension, and that additional components contribute marginal explanatory value without substantially altering country assessments.

Cross-validation following Field (2009), whereby we randomly split observations and compared factor loadings across subsets, demonstrated structural stability. The consistency of loadings and explained variance across splits supports the reliability of our component structure.

5.5 Comparative analysis with European studies

Matejková et al. (2024) developed a similar PCA-based food security index for 24 EU countries using 2021 data. Their study reported that the harmonized index of consumer prices (HICP) for food had the greatest impact (weight = 0.131), followed by average protein supply (0.125) and animal-origin protein supply (0.123). These findings partially overlap with our results, though our global sample produces different weighting patterns due to greater cross-national variation.

Their identification of three underlying factors, economic wellbeing (50.2% variance), health/nutrition (16.5% variance), and inclusive stability (11.7% variance), provides a more granular dimensional structure than our single-component solution. This discrepancy likely reflects their smaller, more homogeneous sample (24 EU countries) vs. our global coverage (122 countries across all development levels). Greater heterogeneity in global data may collapse these dimensions into a single dominant gradient.

Matejková et al. (2024) found that Ireland ranked highest among EU countries, while Bulgaria scored lowest. Slovakia ranked 22nd of 24 countries, attributed primarily to lowest protein supply including animal-derived proteins. Our global analysis cannot directly validate these within-Europe rankings, but the emphasis on protein indicators as discriminatory variables aligns with our findings.

Their observation that Lithuania outperformed other post-socialist countries, attributed to high fish and seafood consumption (De Boer and Aiking, 2018), illustrates how specific dietary patterns can influence index performance. This contrasts with Dudek et al. (2021), who identified Lithuania as least food-secure among CEE countries using household survey data. The discrepancy reveals methodological sensitivity: macro-level supply indicators vs. micro-level food insecurity experience scales may produce divergent assessments.

5.6 Implications of index construction methodology

The objective weighting approach via PCA offers advantages over subjective expert-assigned weights. By allowing data structure to determine indicator importance, we avoid potential biases in weight selection. However, this approach also means that indicators with greater variance across countries receive higher implicit weight. In globally diverse samples, this may overemphasize dimensions that vary widely (e.g., protein supply ranging from severe deficiency to abundance) while underweighting more uniformly distributed indicators.

The 3-year moving average approach, consistent with FAO reporting standards, smooths short-term fluctuations but may also obscure rapid changes in food security status. During acute crises (e.g., sudden conflict, natural disasters), our index would lag in detecting deterioration. This temporal smoothing represents a trade-off between stability and responsiveness.

Linear interpolation for missing data (∼10% of observations) assumes smooth temporal transitions. In countries experiencing abrupt regime changes or conflict, this assumption may introduce measurement error. However, alternative approaches (deletion, multiple imputation) present their own limitations, and our sensitivity analyses suggest these interpolations do not substantially affect results.

5.7 The role of governance and institutions

The moderate-to-high loading of political stability (0.61) on PC1 warrants closer examination. Governance appears to function as an enabling condition for food security, rather than a direct determinant. Stable political environments facilitate trade flows, enable consistent agricultural investment, and support effective safety net implementation (Kaufmann et al., 2002; Bonuedi et al., 2020).

The clustering results reinforce this interpretation. Countries scoring higher food security tiers typically exhibit strong institutions and governance indicators, independent of income level. This suggests that institutional quality may mediate the relationship between economic resources and food security outcomes, though establishing this causal pathway requires methods beyond our descriptive analysis.

However, the governance-food security association should not be interpreted as deterministic. Some countries with moderate governance scores achieve relatively high food security through targeted investments in agriculture and rural infrastructure. This heterogeneity suggests multiple pathways to food security improvement exist, with governance representing one important but not exclusively necessary condition.

5.8 Data availability and measurement gaps

The exclusion of multiple Pacific Island nations due to missing data represents a known limitation. These omissions stem from data availability constraints rather than methodological choice, but they introduce potential selection bias. Countries lacking robust food security data systems may systematically differ from those with complete data, possibly exhibiting weaker statistical capacity, itself a governance indicator (Jerven, 2013).

The absence of reliable indicators from data-sparse regions reflects both technical challenges (infrastructure, survey systems) and political factors (low prioritization of statistical development). This dual challenge means that global food security assessments inevitably underrepresent regions with weakest data infrastructure, potentially creating blind spots where vulnerability is highest (Sandefur and Glassman, 2015).

Our reliance on nationally aggregated data precludes analysis of within-country disparities. Food insecurity often concentrates in specific regions, ethnic groups, or socioeconomic strata that national averages obscure. Urban-rural divides, gender disparities in food access, and seasonal variation represent dimensions our methodology cannot capture.

5.9 Limitations and measurement challenges

The PCA framework, while statistically robust, cannot capture certain complex food security phenomena. Informal food systems, including urban agriculture, wild food harvesting, and community-based distribution networks, operate outside official statistics. In many developing countries, these informal systems provide substantial portions of dietary intake, yet remain invisible to national-level indicators.

Intra-household allocation represents another unmeasured dimension. Household-level food availability does not guarantee equitable distribution among household members. Gender disparities in food access, preferential feeding of certain children, and seasonal variation in household dynamics all affect individual food security but escape detection in aggregate indicators.

Cultural dietary variation presents measurement challenges for indices emphasizing protein supply. Different dietary traditions rely on varied protein sources (legumes, dairy, fish, meat) with distinct nutritional profiles. An index heavily weighted toward animal protein may implicitly favor certain dietary patterns, potentially misrepresenting food security in cultures with predominantly plant-based traditions.

The explained variance of 60.36% indicates that our model captures the majority but not entirety of food security variation. The unexplained 40% likely includes: localized distribution inefficiencies, food waste at various supply chain stages, dietary knowledge and preparation practices, health status affecting nutrient absorption, and water quality impacting food utilization. Future research integrating qualitative case studies, spatial econometrics, or mixed methods designs could illuminate these unmeasured dimensions.

5.10 Temporal trends and responsiveness

The 2000–2021 timeframe encompasses multiple global food security shocks: the 2007–2008 food price crisis, the 2011–2012 Horn of Africa drought, the 2015–2016 El Niño, and the COVID-19 pandemic. Our 3-year moving averages smooth these fluctuations, revealing medium-term trends rather than acute crisis responses.

Countries showing upward FSI mobility over time (e.g., Vietnam, Rwanda) generally correspond with documented agricultural development investments and rural poverty reduction efforts. Conversely, countries experiencing FSI declines (e.g., Venezuela, Yemen) align with well-documented conflict, economic collapse, or institutional deterioration. These patterns support the index's construct validity as a measure of food security trajectories.

However, the index's responsiveness to short-term shocks remains limited. During acute food crises, real-time monitoring requires more frequent data collection and alternative indicators (e.g., market prices, household surveys) than our methodology employs. The FSI functions better as a medium-term tracking tool than as an early warning system.

5.11 Synthesis and contribution

This Food Security Index contributes to existing food security measurement literature by: (1) providing objective, data-driven indicator weights through PCA; (2) covering 122 countries over 22 years, enabling broad temporal and geographic comparison; (3) integrating all four FAO dimensions into a single metric; and (4) validating results against established indices (GFSI) while offering clustering-based segmentation for policy targeting.

The index reveals that food security operates primarily as a unidimensional construct at the macro level, despite conceptual multidimensionality. Nutritional quality indicators (protein supply, dietary adequacy) define this dimension most strongly, while governance and production stability contribute moderately. Regional clustering patterns challenge income-deterministic models, suggesting institutional quality and policy effectiveness moderate the income-food security relationship.

Methodological transparency, including reporting of excluded variables, sensitivity analyses, and validation procedures, strengthens the index's credibility as a monitoring tool. The strong correlation with GFSI ($\rho = 0.81$) confirms convergent validity, while clustering adds actionable segmentation for identifying peer countries and targeting interventions.

Nonetheless, approximately 40% of unexplained variance and the inability to capture informal systems, intra-household dynamics, and cultural dietary variation represent inherent limitations of macro-level indices. Future research should integrate qualitative methods, household-level data, and spatial analysis to address these gaps and magnify our understanding of food security's multifaceted nature across diverse contexts.

6 Conclusion

This study developed a multidimensional Food Security Index for 122 countries spanning 2000–2021 using PCA to derive indicator weights objectively from the data structure rather than relying on expert judgment. The index integrates eight indicators representing the four FAO pillars of availability, access, utilization, and stability, with the first principal component explaining 60.36 percent of total variance. Strong convergent validity with the Global Food Security Index confirms that the FSI captures core food security dimensions while offering greater methodological transparency and temporal consistency than subjective weighting approaches.

The analysis reveals several important patterns in global food security. First, nutritional quality indicators, particularly average protein supply and dietary supply adequacy, most strongly define the food security dimension. This finding suggests that diet quality rather than mere caloric quantity anchors food security outcomes at the national level. Second, political stability demonstrates a moderately high positive loading, positioning governance and institutional resilience among the more influential structural determinants. While our methodology does not establish causal direction, this pattern indicates that institutional capacity correlates strongly with food security performance across countries. Third, systemic volatility, captured through food production variability, differentiates countries along the food security continuum, featuring the importance of stability as a distinct dimension.

The clustering analysis reveals persistent regional inequalities. Most Sub Saharan African and South Asian countries fall into very low or low food security clusters, reflecting material deficits compounded by structural vulnerabilities including institutional fragility and climate exposure. Conversely, Western European, East Asian, and Oceanic countries consistently cluster in high food security categories, supported by resilient governance and infrastructure. Importantly, national income alone does not determine food security status. Several upper-middle-income countries including Venezuela, Brazil, and South Africa cluster in low food security categories, likely reflecting systemic inequality and governance gaps. Meanwhile, some lower-income countries such as Vietnam and Rwanda achieve relatively higher cluster positions, suggesting that institutional quality and policy effectiveness may moderate the income food security relationship.

Recent global shocks provide suggestive evidence of differential resilience. Countries with stronger governance scores experienced smaller FSI ranking changes during COVID 19 disruptions, while those with high import dependence and weak institutions fell into lower clusters following Ukraine war related disruptions. These patterns suggest associations between governance strength and shock absorption capacity, though causal mechanisms remain untested in our framework.

This research contributes methodologically by demonstrating that PCA derived weights produce food security assessments comparable to expert weighted indices while enhancing objectivity and replicability. The clustering approach adds practical value by segmenting countries into actionable tiers for comparative analysis and peer identification. Cross validation and sensitivity analyses confirm structural stability across data splits and component specifications, supporting the reliability of our findings.

However, important limitations constrain interpretation. Approximately 40 percent of variance remains unexplained, reflecting phenomena our eight macro level indicators cannot capture. These include informal food systems, intra household allocation dynamics, cultural dietary preferences, food waste patterns, and localized distribution inefficiencies. National aggregation obscures within country disparities across regions, ethnic groups, and socioeconomic strata. The 3 year moving average approach smooths short term volatility but reduces responsiveness to acute crises.

The exclusion of Pacific Island nations and other countries with missing data introduces potential selection bias. Data gaps reflect both technical constraints including survey infrastructure and political factors such as low statistical capacity prioritization. This means global assessments inevitably underrepresent regions with the weakest data systems, potentially where vulnerability is highest. Addressing this requires sustained investment in national data systems, not merely improved index methodology.

Finally, the correlational nature of PCA precludes causal inference. While our results identify associations between governance, nutritional indicators, and food security outcomes, establishing causal pathways requires alternative methods including instrumental variables, difference in differences designs, or randomized evaluations. These approaches remain beyond this study's scope but represent important directions for future research.

The FSI demonstrates that objective weighting methods can produce valid food security assessments while maintaining transparency about indicator contributions. The dominance of protein supply and dietary adequacy in component loadings suggests that future indices should prioritize nutritional quality metrics alongside traditional availability measures. The moderate importance of governance indicators reinforces that food security measurement should extend beyond agricultural production to encompass institutional dimensions.

For global monitoring efforts, the strong correlation with the Global Food Security Index validates PCA based approaches as viable alternatives to expert weighted systems. The clustering methodology offers practical segmentation for identifying peer countries and targeting monitoring resources. However, the substantial unexplained variance accentuates the need for complementary approaches. Household level surveys, qualitative case studies, and subnational disaggregation remain essential for capturing food security dimensions that national aggregates miss.

6.1 Policy implications

While our methodology establishes associations rather than causal mechanisms, the empirical patterns observed suggest several considerations for policy design. These implications should be understood as hypotheses warranting further investigation rather than definitive prescriptions, given the correlational nature of our analysis and the substantial unexplained variance in our model.

The clustering analysis reveals that countries at different food security levels face distinct challenges, suggesting that intervention priorities should vary systematically across tiers. However, the heterogeneity within clusters and the unexplained variance caution against overly rigid tier based prescriptions.

For very low and low food security contexts, predominantly low-income Sub-Saharan African and South Asian nations, the clustering patterns reflect foundational infrastructure deficits and governance challenges. The strong loadings of production variability and the negative loadings of undernourishment suggest that these contexts face both chronic deficits and acute volatility. This pattern indicates that interventions addressing both baseline capacity and shock resilience may be necessary. The moderate loading of political stability suggests that governance constraints may limit intervention effectiveness in fragile settings. Program design should therefore account for implementation constraints including corruption risks, weak administrative capacity, and institutional instability. Phased approaches that begin with simpler, more decentralized interventions such as community managed storage facilities or farmer cooperatives may prove more feasible than comprehensive reforms, though empirical validation of this sequencing hypothesis requires further evaluation.

For moderate food security contexts, including many lower-middle-income nations in Latin America and Southeast Asia, baseline availability may be adequate, but stability dimensions remain problematic. The production variability loading suggests that these countries may benefit particularly from risk management mechanisms. Policies that scale up index-based insurance schemes, integrate early warning systems with adaptive social protection, and incentivize production diversification could buffer against climate and market volatility. At the regional level, trade diversification and strategic food reserves may help buffer against global price spikes, though the optimal design of such mechanisms remains context dependent.

For high food security contexts, strong aggregate scores coexist with pockets of deprivation that national averages obscure. The high loadings of protein supply and dietary adequacy suggest that even in food abundant settings, nutritional quality and access remain differentiating factors. This implies that subnational disaggregation and targeted interventions may be necessary even in high performing countries. Policies that mandate large scale fortification programs and deploy targeted interventions such as school meal enrichment or mobile nutrition clinics in underserved regions could address these gaps. Disaggregating the FSI to subnational levels would illuminate these disparities and enable precision in policy design.

The political stability loading and the clustering patterns showing income governance interactions suggest that institutional development may represent a critical enabling condition for food security improvements. However, our methodology cannot isolate whether governance directly strengthens food security, whether both reflect common development processes, or whether reverse causality operates. This ambiguity has important implications. If governance improvements causally improve food security, then institutional reforms should receive priority in intervention portfolios. If the relationship is spurious or reverse causal, then direct food security investments might yield better returns. Distinguishing these pathways requires methods beyond correlational analysis.

The cases of Vietnam and Rwanda, lower-income countries achieving higher cluster positions, suggest that governance quality may moderate income effects. However, our analysis does not identify which specific governance dimensions matter most. Investments in statistical capacity, agricultural extension systems, transparent procurement, or corruption control may have differential impacts, warranting targeted evaluation.

The dominant loadings of protein supply and dietary adequacy indicate that nutritional quality strongly differentiates food security levels. This pattern suggests that interventions focused solely on caloric availability may miss critical nutritional dimensions. However, our indicators measure supply side availability rather than actual consumption or nutritional status, leaving uncertain whether supply increases translate to improved individual nutrition. The strong performance of these indicators implies that policies promoting dietary diversity, protein access from varied sources, and micronutrient availability align with the construct our index measures. However, the optimal mechanisms for achieving nutritional improvements, whether through production diversification, fortification, market development, or consumer education, remain empirically underexplored and likely context dependent.

Cultural dietary variation, which our model cannot capture, may significantly affect how supply side interventions translate to nutritional outcomes. Programs that ignore local food preferences, preparation practices, and dietary traditions may fail despite improving measured availability. This limitation underlines the need for culturally adapted approaches informed by ethnographic and household level research.

The exclusion of Pacific Island nations and other data sparse regions emphasizes a critical policy challenge. Evidence based intervention targeting depends on measurement systems that systematically underrepresent the most vulnerable populations. This creates a problematic feedback loop where data gaps reduce visibility, which reduces resource allocation, which perpetuates gaps. Addressing this requires sustained investment in national statistical systems, particularly survey infrastructure, training, and institutional capacity. However, such investments compete with direct service provision for scarce resources. International coordination could reduce measurement costs through standardized protocols, shared methodologies, and technical assistance. Harmonization must balance comparability benefits against local contextual factors that may require adapted indicators or approaches.

The Food Security Index provides a diagnostic tool for monitoring food security trends, identifying peer countries, and stratifying populations by food security status. Its methodological transparency and validation against established indices support its use in global monitoring systems. However, translating descriptive patterns into prescriptive policy requires additional evidence regarding causal mechanisms, implementation constraints, and context specific factors our methodology cannot capture.

Policymakers should interpret FSI results as identifying associations warranting further investigation rather than definitive causal relationships. The clustering approach offers a useful stratification framework for tailoring research priorities and monitoring intensity across contexts, but optimal interventions within each tier require context specific evaluation. The strong correlation between governance indicators and food security outcomes suggests institutional development merits attention, though specific governance reforms require targeted study.

Most importantly, the substantial unexplained variance and systematic data gaps affecting vulnerable populations emphasize that index-based monitoring must be complemented by household surveys, qualitative research, and participatory methods. Food security remains a complex, multidimensional phenomenon that quantitative indices usefully but incompletely measure. Effective policy requires integrating multiple evidence streams rather than relying solely on macro level indices, however methodologically rigorous those indices may be.

6.2 Future research directions

Several research priorities emerge from this analysis. First, mixed methods designs combining quantitative indices with qualitative investigation could illuminate the 40% unexplained variance, particularly regarding informal food systems, intra-household dynamics, and cultural dietary practices. Ethnographic studies in diverse contexts would enrich understanding of how households cope in the face of food insecurity beyond what macro indicators reveal.

Second, causal inference methods should examine pathways linking governance, markets, and nutrition outcomes. Natural experiments, instrumental variables, or quasi-experimental designs could test whether governance improvements causally boost food security or whether both reflect common underlying factors. Similarly, investigating mechanisms through which production volatility translates to food insecurity would inform shock mitigation strategies.

Third, subnational disaggregation of the FSI could reveal within-country disparities obscured by national averages. Constructing regional or district-level indices would enable identification of vulnerable populations in otherwise food-secure countries and high-performing regions in food-insecure countries. This would support more targeted resource allocation.

Fourth, incorporating additional indicators, particularly those capturing food waste, water quality, dietary knowledge, and health system effectiveness, could reduce unexplained variance. However, data availability constraints currently limit such expansion, underscoring the need for improved global food security statistics.

Fifth, temporal dynamics warrant deeper investigation. Panel econometric methods could examine how countries transition between food security clusters over time and identify factors accelerating or impeding such transitions. Understanding mobility patterns would inform whether countries face persistent traps or whether pathways to improvement exist.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.mendeley.com/v1/datasets/publish-confirmation/swr32nynts/1.

Author contributions

OO: Writing – review & editing, Formal analysis, Methodology, Writing – original draft, Data curation, Validation, Visualization, Conceptualization. BT: Project administration, Validation, Writing – original draft, Supervision, Writing – review & editing.

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Conflict of interest

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Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. During the preparation of this work, the author(s) used ChatGPT by OpenAI to improve the readability, clarity, and structure of the manuscript. After using this tool, the author(s) reviewed and edited the content thoroughly and take full responsibility for the content of the published article.

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Appendix

TABLE A1 Correlation matrix of the 15 indicators.

Variable	Av_ diet _ supply	Av_ protein _sup	p_ undernourish	Cerea _ impdep	per_i rrigation	V_fd_ imp_ merc_ exp	percap_ fdprod var	fsupp_ var	Prev_ obst	prev_ anem	Gross_ per capita Food_ Prod_ Index	Food_ vol	Food_ def_ per_ cap	Food_ val_ Mov_ Av
Av_diet_ supply	1.000													
Av_ protein_sup	0.83	1.00												
p_ undernourish	−0.82	−0.75	1.00											
cerea_ impdep	−0.14	−0.17	0.18	1.00										
per_ irrigation	0.07	0.09	−0.15	0.31	1.00									
V_fd_imp_ merc _exp	−0.28	−0.31	0.34	0.12	0.00	1.00								
percap_ fdprodvar	0.23	0.31	−0.29	−0.52	−0.10	−0.12	1.00							
fsupp_var	−0.15	−0.15	0.12	0.06	0.06	0.12	0.05	1.00						
Prev_obst	0.58	0.60	−0.55	−0.10	0.22	−0.24	0.34	0.02	1.00					
prev_anem	−0.49	−0.66	0.56	0.20	−0.15	0.32	−0.33	0.12	−0.55	1.00				
Gross_per capita Food_ Prod_Index	0.09	0.09	−0.07	0.15	0.16	0.08	0.03	0.03	0.13	−0.03	1.00			
Food_vol	−0.07	−0.05	0.06	0.03	0.02	−0.01	−0.02	0.22	0.04	−0.01	−0.01	1.00		
Food_def_ per_cap	−0.93	−0.83	0.76	0.16	−0.02	0.27	−0.27	0.14	−0.61	0.51	0.01	0.07	1.00	
Food_val_ Mov_Av	0.07	0.06	−0.07	−0.07	−0.01	−0.05	−0.03	−0.06	0.04	−0.08	−0.04	−0.01	−0.10	1.00

The gray color implies variables with correlations below 0.3 that is <0.3.