

Ecological Debt and Food Security: A Dynamic Panel Analysis of Indonesian Provinces

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JEL Classification:

Q56

Q18

C23

O13

Received: 02 April 2026

Revised: 13 June 2026

Accepted: 18 June 2026

Published online: September 2026

Abstract

Research Originality: This study positions multidimensional environmental quality (air, water, and marine ecosystems) as a key determinant of food security within a unified provincial framework, employing the GMM approach to address persistence and endogeneity.

Research Objectives: To assess the influence of environmental quality on food security across Indonesian provinces and identify socio-economic barriers to regional resilience.

Research Methods: Using panel data from 34 provinces during 2019–2024, the study examines the Food Security Index (FSI) in relation to the Environmental Quality Index (EQI), its sub-indices, and socio-economic controls, including agricultural GRDP, poverty, and unemployment.

Empirical Results: Food security exhibits strong persistence, indicating path dependence. Overall environmental quality has a negative short-run effect, reflecting an ecological debt pattern driven by resource exploitation. In contrast, water and air quality improve food security, while poverty and unemployment significantly constrain outcomes.

Implications: Indonesia should shift from a production-oriented to a resilience-oriented food security strategy by promoting sustainable intensification, improving water and marine resource management, and strengthening social protection. Given regional heterogeneity, place-based policies are essential to enhance long-term food system resilience and achieve SDG 2.

Keywords:

environmental quality; food system; generalized method of moments; poverty

How to Cite:

Hoeriyah, L., & Musliha, C. (2026). Ecological Debt and Food Security: A Dynamic Panel Analysis of Indonesian Province. *Etikonomi*, 25(2), 651 – 666. <https://doi.org/10.15408/etk.v25i2.50580>.

INTRODUCTION

Food security remains a complex and multidimensional challenge, particularly in developing countries, where it is shaped not only by food availability and access but also by stability and utilization (Saxena, 2025). According to the Regulation of the National Food Agency of the Republic of Indonesia, food security is defined as a condition in which food needs—ranging from the national to the individual level—are adequately fulfilled through sufficient food availability. This availability must cover not only adequate quantity and quality but also safety, diversity, nutritional value, equitable distribution, and affordability for all groups in society, while respecting religious, belief, and cultural values (Fanzo, 2015). Food security is also closely related to sustainable development, as limited access to food can increase poverty, social vulnerability, and economic instability (FAO, 2025; Subekti et al., 2024). Moreover, food security has become an increasing global concern due to population growth, environmental degradation, and climate change pressures that threaten the sustainability of food systems (Varzakas & Smaoui, 2024).

Traditionally, efforts to improve food security have focused on increasing agricultural productivity and strengthening socio-economic capacity (Sari et al., 2024). However, recent studies suggest that such conventional approaches are no longer sufficient to address escalating environmental challenges (El Bilali et al., 2020; Richardson et al., 2018). In this context, environmental factors—particularly climate change—play a critical role in influencing food security outcomes. Temperature changes, shifting rainfall patterns, and more frequent extreme weather events directly affect agricultural productivity and, consequently, food availability (Kumar et al., 2018; Liu et al., 2025). Climate projections indicate that these changes may significantly reduce crop yields in developing regions, thereby increasing the risk of food insecurity (El Bilali et al., 2020; Susandi et al., 2023; Su et al., 2026). Furthermore, environmental degradation, biodiversity loss, and ecosystem disruption can weaken the long-term resilience of food systems (Ali et al., 2026; Mogollón et al., 2026). Consequently, an important academic debate has emerged regarding whether food security is primarily driven by socio-economic and production factors or increasingly constrained by environmental degradation.

In Indonesia, food security challenges remain significant despite substantial agricultural potential. According to the 2024 Global Hunger Index (GHI), Indonesia ranks 77th out of 127 countries, placing it in the moderate hunger category. Similarly, its position in the Global Food Security Index (GFSI) indicates that Indonesia still lags behind several Southeast Asian countries. Compared with other Southeast Asian countries, Indonesia still lags. Indonesia ranks below Myanmar, Cambodia, the Philippines, Malaysia, Vietnam, and Thailand, suggesting that hunger levels in those countries are relatively lower. This suggests that Indonesia needs to strengthen its food security strategies more comprehensively. These conditions suggest that improvements in food production alone are not sufficient to ensure food security. Structural challenges—such as uneven food distribution, regional disparities, and vulnerability to environmental shocks—continue to hinder progress toward achieving sustainable food systems (Zou et al., 2023). Recent studies also highlight that Southeast Asia is among the regions most vulnerable to climate-

induced food insecurity due to its dependence on climate-sensitive agricultural systems (Su et al., 2026).

Existing empirical studies provide mixed evidence regarding the determinants of food security. A large body of research emphasizes agricultural productivity, trade, and socio-economic variables as the primary drivers of food security (Juliannisa et al., 2025; Sundram, 2023; Ye, 2023). For instance, Juliannisa et al. (2025) highlight that regional food security in Indonesia is strongly influenced by agricultural productivity and infrastructure development, with improvements in production capacity and distribution systems significantly enhancing food availability and access. Similarly, Sundram (2023) underscores the role of trade openness and economic growth in strengthening food security, arguing that greater market integration and higher incomes enable households to access sufficient, nutritious food. In line with this, Ye (2023) finds that socio-economic factors, such as income, education, and population dynamics, play a crucial role in shaping food security outcomes, particularly in developing countries. These studies collectively suggest that economic and production-related factors remain central in explaining food security performance across regions.

In contrast, other studies emphasize the growing role of environmental factors, such as climate change, land degradation, and natural resource depletion, in influencing food system outcomes (Dermoredjo et al., 2024; Malau et al., 2021). Dermoredjo et al. (2024) demonstrate that environmental degradation, particularly declining land quality and increasing climate variability, significantly reduces agricultural productivity and disrupts food supply stability in Indonesia. Their findings highlight that regions experiencing higher environmental stress tend to face greater challenges in maintaining sustainable food systems. Similarly, Malau et al. (2021) show that climate-related shocks, such as floods and droughts, increase food prices and disrupt food distribution systems. More recent evidence further confirms that environmental degradation has become a critical threat to food system resilience and sustainability (Ali et al., 2026; Elechi et al., 2022). Despite this growing recognition, environmental quality is still often treated as a secondary or external factor rather than a central determinant. As a result, integrated empirical studies have insufficiently explored the relationship between environmental conditions and food security.

To address this research gap, this study positions environmental quality as a central explanatory variable in analyzing food security outcomes across Indonesian provinces. The novelty of this research lies in its conceptual and empirical shift in examining food security by prioritizing environmental quality as a primary driver, rather than a complementary factor. Unlike previous studies that are predominantly production- or economy-centered, this study integrates multiple environmental dimensions—air, water, and marine ecosystems—into a unified analytical framework. Furthermore, it uses provincial-level panel data and applies the Generalized Method of Moments (GMM) approach to capture dynamic effects and address potential endogeneity, providing a more robust empirical analysis (Gobezie & Boka, 2023; Mtar et al., 2025; Rahaman & Islam, 2025). Accordingly, this study examines the extent to which environmental quality influences food security across Indonesia's provinces.

This study makes two main contributions. First, from a theoretical perspective, it deepens understanding of the relationship between environmental quality and food security, moving beyond the conventional production-focused focus of previous studies. Second, from an empirical perspective, it provides new evidence by employing a dynamic econometric approach and provincial-level data, which remain relatively underutilized in the Indonesian context. Furthermore, the findings are expected to support the formulation of more integrated policies linking environmental management and food security, particularly in advancing the achievement of the Sustainable Development Goals (SDGs).

METHODS

This study uses secondary panel data from 34 Indonesian provinces during 2019–2024, obtained from the Central Bureau of Statistics, the National Food Agency, and the Ministry of Environment and Forestry. Due to data limitations, the analysis excludes four newly established provinces—South Papua, Central Papua, Highland Papua, and Southwest Papua. The dependent variable is the Food Security Index (FSI), which the National Food Agency has published annually since 2019. As a composite indicator, the FSI captures the dimensions of food availability, affordability, and utilization, providing a comprehensive measure of provincial food security. The main explanatory variable is the Environmental Quality Index (EQI), which reflects overall environmental conditions through its components of water, air, land, and marine quality. To identify specific environmental channels, this study additionally includes the Water Quality Index, Air Quality Index, and Marine Water Quality Index. Economic and social controls include the Agricultural Sector's Gross Regional Domestic Product (GRDP), the number of poor people, and the unemployment rate. These variables account for structural economic conditions and socio-economic vulnerabilities that may influence food security outcomes. Table 1 provides a more detailed explanation of the variables used in this study.

To estimate the dynamic impact of environmental and socioeconomic factors on food security, this study employs the Generalized Method of Moments (GMM) for panel data. The model is specified as follows:

$$\text{LogFSI}_{it} = \alpha_0 + \alpha_1 \text{LogFSI}_{i,t-1} + \alpha_2 \text{LogENVIR}_{it} + \alpha_3 \text{LogWATER}_{it} + \alpha_4 \text{LogAIR}_{it} + \alpha_5 \text{LogMARINE}_{it} + \alpha_6 \text{LogAGRI}_{it} + \alpha_7 \text{LogPOOR}_{it} + \alpha_8 \text{UNEMPL}_{it} + \varepsilon_{it}$$

where LogFSI_{it} is the natural logarithm of the Food Security Index; $\text{LogFSI}_{i,t-1}$ is its one-period lag, reflecting the dynamic nature of food security, where current levels are influenced by past performance; LogENVIR_{it} , LogWATER_{it} , LogAIR_{it} , and LogMARINE_{it} are the natural logarithms of the Environmental Quality Index, Water Quality Index, Air Quality Index, and Marine Water Quality Index, respectively, used as proxies for environmental variables; LogAGRI_{it} is the natural logarithm of the Gross Regional Domestic Product for the agricultural sector; LogPOOR_{it} is the natural logarithm of the number of poor (thousands); UNEMPL_{it} is the unemployment rate (percent); i denotes the country and t represents the time period; ε_{it} is the error term; α_0 is the intercept; and α_n is slope ($n = 1, 2, \dots$).

The inclusion of a lagged dependent variable ($LogFSI_{i,t-1}$) as an explanatory variable introduces dynamic panel bias. This occurs because the lagged variable is inherently correlated with the province-specific fixed effects in the error term. Consequently, standard estimation techniques such as Pooled Ordinary Least Squares (POLS) and static Fixed Effects (FE) models yield inconsistent and biased parameter estimates (Fusco et al., 2020; Mulusew & Mingyong, 2023). The GMM approach, specifically developed for dynamic panels, addresses these issues by using internal instruments (lagged values of the variables) to control for endogeneity (Ullah et al., 2018).

Table 1. Operational Definition of Variables

Variables	Definition	Symbol	Unit of Measurement	Data Source
Food Security Index	The food security status of a region	FSI	Index	National Food Agency
Environmental Quality Index	An indicator representing the environmental quality of a region at a specific point in time	ENVIR	Index	Ministry of Environment and Forestry
Water Quality Index	Composite measure of water quality parameters in a region at a given time	WATER	Index	Ministry of Environment and Forestry
Air Quality Index	Composite measure of air quality parameters in a region at a given time	AIR	Index	Ministry of Environment and Forestry
Marine Water Quality Index	Composite measure of marine water quality parameters in a region at a given time	MARINE	Index	Ministry of Environment and Forestry
Gross Regional Domestic Product for the agricultural sector	An economic activity sector that includes agriculture (covering food crops, horticulture, plantations, and livestock), forestry, and fisheries, which reflects the gross value added generated from all economic activities in that sector	AGRI	In billion rupiahs	Central Bureau of Statistics
Number of poor	The number of poor people refers to the population whose average monthly per capita expenditure falls below the poverty line	POOR	In thousands of people	Central Bureau of Statistics
Unemployment rate	The percentage of the unemployed population relative to the total labor force	UNEMPL	Percent	Central Bureau of Statistics

To ensure robust estimation, we employ the two-step System GMM estimator developed by Blundell and Bond in 1998 and Arellano and Bover in 1995, which is superior to the Difference GMM estimator when the time series are persistent (close to a random walk) or when the dataset has a small number of time periods (T) relative to a large number of cross-sectional units (N) (Mulusew & Mingyong, 2023). System GMM

addresses three primary sources of endogeneity—unobserved heterogeneity, simultaneity, and dynamic endogeneity—by using internal instruments (lagged variable values) and transforming the data through forward orthogonal deviations. The two-step approach is adopted because it is more asymptotically efficient and more robust to heteroskedasticity and panel-specific autocorrelation than the one-step estimator (Mulusew & Mingyong, 2023; Ullah et al., 2018; Anser et al., 2021).

The validity of the GMM estimates is confirmed through two essential post-estimation diagnostic tests: the Arellano-Bond test for serial correlation and the Sargan test of overidentifying restrictions. The Arellano-Bond test evaluates the null hypothesis of no second-order serial correlation in the first-differenced residuals. While first-order autocorrelation (AR (1)) is expected, the absence of second-order autocorrelation (AR(2)) is critical for confirming that the GMM estimator is consistent. Additionally, the Sargan tests verify the overall validity of the instruments, where a non-significant result ($p > 0.05$) indicates that the instruments are exogenous and not correlated with the error term, thereby justifying the model specification and ensuring the reliability of the results (Mulusew & Mingyong, 2023; Dardeer & Shaheen, 2025; Beyene, 2023; Subramaniam et al., 2019; Ullah et al., 2018).

RESULT AND DISCUSSION

Food security is a key pillar of national resilience shaped by environmental and socio-economic factors. This study finds that agricultural intensification improves short-term food availability but generates ecological trade-offs that reduce overall environmental quality. Water quality, marine water quality, and agricultural sector GRDP emerge as the main long-term drivers of food security in Indonesia, while poverty and unemployment remain persistent structural barriers. These findings suggest that achieving Zero Hunger requires a shift from resource-intensive production toward sustainable resource management.

Table 2. Descriptive Statistics

	Mean	Std. Error	Median	Std. Deviation	Kurtosis	Skewness	Minimum	Maximum
FSI	72.08	0.75	74.06	10.73	3.90	-1.74	25.13	88.23
AGRI	41109.28	3149.53	21720.28	44984.25	1.62	1.66	1398.22	177789.80
Growth	4.07	0.29	4.63	4.11	7.21	0.48	-15.74	22.94
Poor	762.36	74.54	346.98	1064.65	5.10	2.48	47.83	4572.73
Poverty	10.26	0.36	8.70	5.21	1.10	1.15	3.47	27.53
Unempl	5.05	0.12	4.68	1.71	1.21	0.92	1.57	10.95
Envir	71.87	0.48	72.80	6.89	2.01	-1.13	42.84	84.22
Water	54.10	0.40	54.64	5.65	0.62	-0.52	35.37	69.29
Air	88.97	0.40	90.39	5.74	5.50	-2.26	66.52	96.41
Marine	78.74	0.54	81.28	7.74	0.02	-0.85	52.65	93.88

Descriptive analysis (Table 2) shows that the Food Security Index (FSI) averages 72.08, indicating relatively strong food security across provinces. However, a standard deviation of 10.73 and negative skewness (-1.74) reveal substantial regional disparities, with several provinces exhibiting considerably lower food security levels. This pattern is consistent with the National Food Agency's 2024 classification, which places Papua in the Vulnerable category, West Papua in the Somewhat Vulnerable category, and Maluku and North Maluku in the Somewhat Resilient category, while most other provinces are classified as Resilient or Very Resilient.

Socio-economic indicators also reveal significant inequality. Agricultural sector GRDP is highly concentrated across regions, as reflected by a large gap between mean and median values and strong positive skewness, a pattern commonly observed in developing economies (Affoh et al., 2022; Abdullah et al., 2017). Economic growth averages 4.07% but varies substantially, likely reflecting external shocks such as the COVID-19 pandemic. Meanwhile, poverty and unemployment remain important structural constraints. The concentration of poor populations in specific regions reinforces previous findings that limited income and purchasing power are major obstacles to food security (Allee et al., 2021; Abdullah et al., 2017; Nicholson et al., 2021; Subramaniam et al., 2019; Akbari et al., 2022).

Environmental indicators provide further insight into the ecological foundations of food security. The Environmental Quality Index averages 71.87, with air quality recording the highest score (88.97) and water quality the lowest (54.10). This highlights water quality as a critical bottleneck to sustainable agricultural productivity, as clean water is essential for irrigation and safe food consumption (Allee et al., 2021; Ammar et al., 2022; Affoh et al., 2022). Marine water quality averages 78.74, underscoring its importance for coastal communities that depend on fisheries for animal protein (Akbari et al., 2022). The negative skewness across environmental indicators suggests widespread ecological degradation, indicating that short-term production gains may come at the expense of long-term environmental sustainability (Zhuang et al., 2022; Akbari et al., 2022).

Spatial evaluation reveals a pronounced imbalance between food security performance and ecological health. Provinces with the lowest environmental quality—including DKI Jakarta, Banten, West Java, DI Yogyakarta, and Central Java—are concentrated in Indonesia's major economic and agricultural centers. Among environmental dimensions, water quality remains the most critical constraint, with an average score far below that of air and marine water quality. This finding reinforces the argument that water availability and quality are fundamental prerequisites for sustainable food systems and the food utilization dimension of food security (Ammar et al., 2022; Ammar et al., 2024).

Figure 1 confirms the expected finding that current food security gains come from environmentally unsustainable intensification. The scatterplot shows a strong negative relationship between food security and environmental quality across Indonesian provinces,

indicating an ecological trade-off: regions with higher Food Security Index (FSI) scores tend to have lower Environmental Quality Index (EQI) scores. This suggests that improvements in food security are often accompanied by natural resource depletion.

Figure 1. The relationship between the Food Security Index and the Environmental Quality Index in 2024

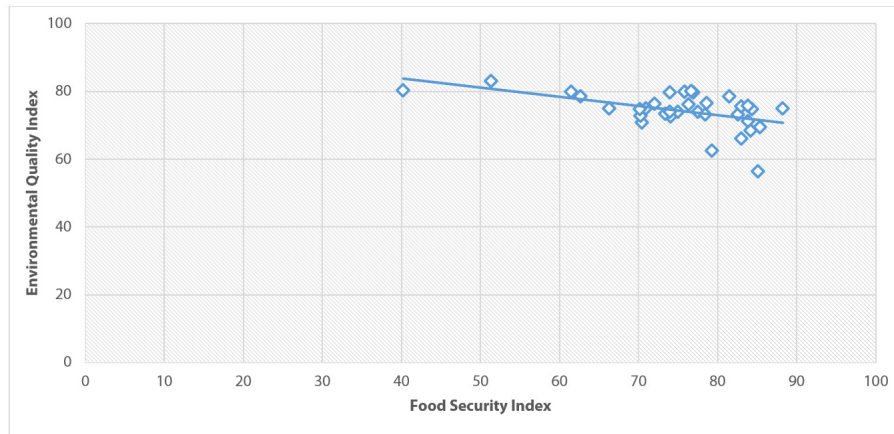


Table 3. The Comparison of Food Security and Environmental Quality Indexes in Indonesia in 2024

Province	FSI	ENVIR	WATER	AIR	MARINE
10 Provinces with the Highest Food Security Index					
Bali	88.23	75.02	61.12	92.12	86.68
Central Java	85.34	69.46	52.03	87.73	78.67
DKI Jakarta	85.13	56.39	41.22	72.59	77.24
West Sumatera	84.32	74.76	53.16	92.27	84.18
DI Yogyakarta	84.15	68.44	42.94	90.44	84.13
East Java	83.86	71.24	54.75	88.09	84.52
South Sulawesi	83.82	75.70	58.50	93.36	84.28
West Java	82.97	66.09	46.86	83.68	88.34
South Kalimantan	82.95	75.59	56.08	96.41	84.27
Lampung	82.58	73.11	62.97	90.94	77.35
10 Provinces with the Lowest Food Security Index					
West Sulawesi	71.99	76.33	55.93	91.46	84.94
East Nusa Tenggara	70.91	75.00	56.59	92.30	84.08
Riau	70.42	70.77	52.69	89.66	77.47
Bangka Belitung Islands	70.21	72.80	57.25	92.13	85.99
Central Kalimantan	70.16	74.80	52.13	92.71	74.47
Riau Islands	66.29	75.05	53.98	92.12	85.53
Maluku	62.68	78.59	56.55	92.42	78.08
North Maluku	61.44	79.94	58.36	93.88	84.79
West Papua Barat	51.36	83.07	63.25	95.17	86.28
Papua	40.21	80.32	52.50	94.40	85.25

This finding is consistent with Zhuang et al. (2022), who argue that land-use change and urbanization frequently create tensions between short-term food security and long-term environmental sustainability. Agricultural intensification and food industrialization largely drive this relationship, as they rely heavily on chemical fertilizers and pesticides. Although these inputs can increase productivity, they also generate environmental externalities such as water eutrophication and soil contamination (Müller et al., 2018). In addition, agricultural expansion and poorly managed food-processing waste contribute significantly to environmental degradation and biodiversity loss (Akbari, 2022).

Global evidence further supports this conclusion, showing that agriculture, forestry, and other land use accounted for 13–21% of anthropogenic greenhouse gas emissions during 2010–2019. Therefore, achieving SDG 2 (Zero Hunger) requires Indonesia to move beyond volume-based production and integrate environmental protection into food security strategies to safeguard the ecological foundations of long-term food production (Dardeer & Shaheen, 2025; Affoh et al., 2022; Beyene, 2023).

As shown in Table 3, provinces with the highest Food Security Index (FSI), such as Bali, Central Java, and DKI Jakarta, generally record lower Environmental Quality Index (EQI) scores. In contrast, Papua and West Papua exhibit the opposite pattern. This inverse relationship is also reflected in indicators of water, air, and marine quality, suggesting that Indonesia's food security achievements are partly sustained by an “ecological debt” model, in which short-term gains in food availability come at the expense of natural capital. The negative relationship between FSI and environmental quality supports the argument that current agricultural intensification is ecologically unsustainable. Intensive use of fertilizers, pesticides, and irrigation may increase productivity but also generate environmental externalities, including ecosystem acidification, nutrient pollution, and contamination of water, soil, and air (Müller, 2018; Taheri et al., 2017). At the same time, environmentally well-preserved regions such as Papua often lack mature food production systems and infrastructure, resulting in lower food security despite high ecological quality (Zhuang et al., 2022). This highlights a structural challenge: productive regions face environmental degradation, while ecologically healthy regions struggle with food access and distribution. These findings reinforce concerns that meeting growing food demand increasingly strains environmental carrying capacity (Akbari, 2022). Therefore, achieving SDG 2 (Zero Hunger) requires a transition toward sustainable intensification, with stronger environmental protection—particularly water quality, which is essential for safe and sustainable food systems (Ammar et al., 2024).

Figure 2 further reveals substantial regional heterogeneity in the food security–environment nexus across Indonesia. Java, Bali, and Nusa Tenggara display the strongest ecological trade-off, combining the highest food security (FSI = 82.03) with the lowest environmental quality (EQI = 68.60), largely due to pressures from population density, industrialization, and intensive agriculture (Allee et al., 2021; Ammar et al., 2024). This finding is consistent with evidence that intensification stabilizes yields but contributes to environmental degradation, particularly through water pollution (Müller,

2018; Ammar et al., 2024). In contrast, Sumatera exhibits a relatively balanced relationship between food security and environmental quality, although water resource pressures remain evident. Kalimantan and Sulawesi show the most resilient profile, maintaining high levels of both food security and environmental quality, supported by superior air quality and more sustainable resource utilization (Zhuang et al., 2022; Garajeh et al., 2023).

The most striking ecological paradox occurs in Maluku and Papua, where environmental quality is highest, but food is lowest. Although ecosystems are relatively well preserved, persistent constraints in infrastructure, market connectivity, and food distribution limit food access and affordability (Akbari et al., 2022; Nicholson et al., 2021; Zhuang et al., 2022). This demonstrates Indonesia’s dual challenge: high-production regions experience ecological degradation, whereas environmentally healthy regions often lack the development needed to ensure adequate food access (Mathenge et al., 2023). Overall, Indonesia’s food security gains frequently coincide with environmental pressures, while regions with weaker food systems tend to maintain stronger ecological conditions. These spatial patterns underscore the need for region-specific policies that integrate environmental protection into food security strategies to safeguard the ecological foundations of long-term food production (Mathenge et al., 2023; Ammar et al., 2024; Allee et al., 2021; Akbari et al., 2022).

Figure 2. Regional Comparison of Food Security and Environmental Quality in Indonesia, 2024

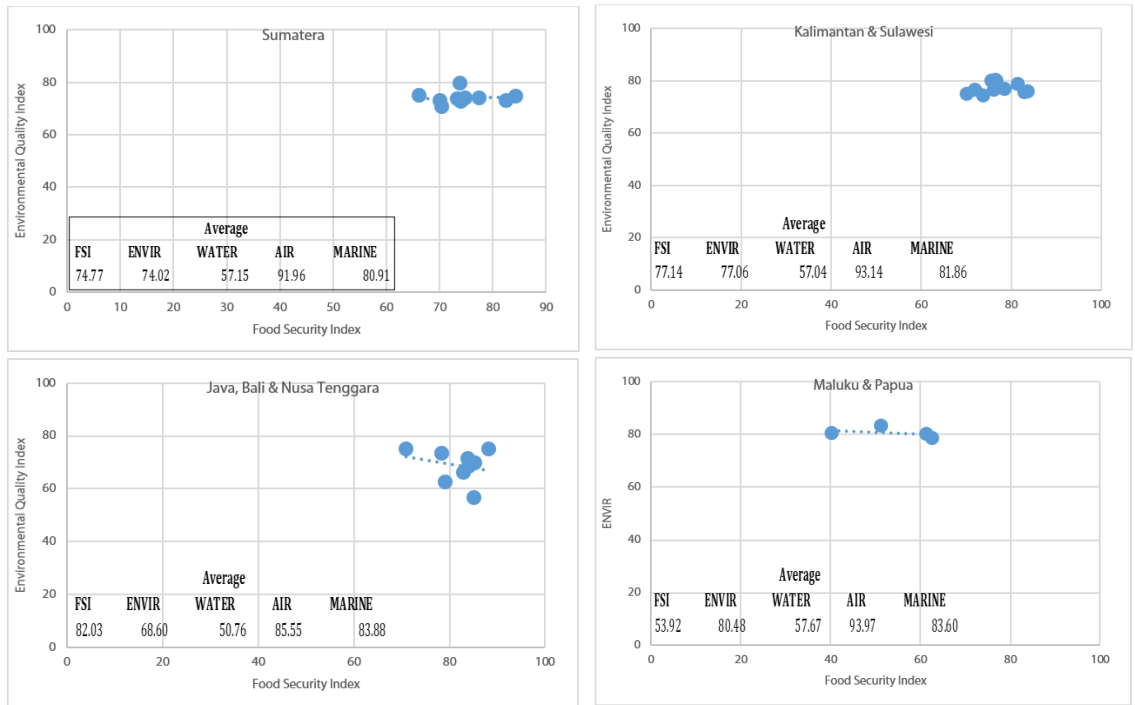


Table 4. Determinants of Food Security: Two-Step System GMM Results

Variables	Dependent Variable = Food Security Index (LogFSI)				Long-Run Estimation of SYS GMM
	FD-GMM	SYS-GMM	FE	PLS	
LogFSI _{t-1}	-0.03710 (0.689)	0.29472*** (0.000)	0.03936 (0.268)	0.733041*** (0.000)	
LogENVIR	-0.42983 (0.159)	-1.20530*** (0.000)	-0.28958 (0.223)	-0.550074*** (0.001)	-1.70897 (0.134)
LogWATER	0.10157 (0.211)	0.33238*** (0.000)	0.03972 (0.548)	0.13052* (0.058)	0.47128* (0.083)
LogAIR	0.42402** (0.038)	0.66907*** (0.009)	0.12115 (0.483)	0.19057 (0.241)	0.94866 (0.188)
LogMARINE	0.00569 (0.336)	0.01101 (0.148)	0.00321 (0.610)	-0.00121 (0.922)	0.01562** (0.016)
LogAGRI	0.02955 (0.573)	0.11177*** (0.000)	0.07837 (0.113)	0.00603 (0.381)	0.15848* (0.059)
LogPOOR	-0.06046** (0.043)	-0.07914*** (0.000)	-0.11202*** (0.000)	-0.99425 (0.527)	-0.11221 (0.131)
UNEMPL	-0.02000*** (0.000)	-0.01005* (0.053)	-0.01654*** (0.000)	-0.00470 (0.122)	-0.01425** (0.037)
Cons	4.11432 (0.000)	3.21233 (0.001)	4.60422 (0.000)	2.13695 (0.000)	
Observation	136	170			
AR(2) test (Prob > z)	(0.1821)	(0.4788)	170	170	
Sargan test (Prob > chi2)	(0.0000)	(0.0000)			

Notes:

***, **, * significant at 1%, 5%, 10%, respectively.

The first row reports the coefficient estimates, while the values in parentheses denote the corresponding probability (p-values).

To ensure the robustness of the findings, we estimated food security determinants using Pooled OLS (PLS), Fixed Effects (FE), First-Difference GMM (FD-GMM), and System GMM (SYS-GMM). While PLS and FE are commonly used benchmark estimators, both are unsuitable for dynamic panel models because including lagged dependent variables generates dynamic panel bias and inconsistent estimates (Ullah et al., 2018). FD-GMM partially addresses this issue but tends to perform poorly under highly persistent data and short time dimensions, where lagged levels become weak instruments (Mulusew & Mingyong, 2023; Fusco et al., 2020). By combining equations in differences and levels, SYS-GMM provides more efficient and reliable estimates while controlling for simultaneity, unobserved heterogeneity, and endogeneity (Mulusew & Mingyong, 2023; Subramaniam et al., 2019). Consequently, the two-step SYS-GMM estimator was selected as the preferred specification.

Model validity was assessed using the Arellano–Bond (AB) and Sargan tests. Although the Sargan statistic is significant, this outcome may reflect its sensitivity to heteroscedasticity and autocorrelation in panel data (Beyene, 2023; Ullah et al., 2018). More importantly, the absence of second-order serial correlation, as indicated by the non-significant AR(2) test, confirms instrument validity and supports the consistency of the SYS-GMM estimates (Mulusew & Mingyong, 2023; Beyene, 2023). The SYS-

GMM results show strong persistence in food security, as indicated by the positive and significant coefficient on the lagged Food Security Index. This finding indicates clear path dependence: regions with stronger past food security performance are more likely to sustain favorable outcomes over time. Food security therefore reflects a cumulative structural process rather than merely short-term agricultural production outcomes (Fusco et al., 2020; Dardeer & Shaheen, 2025). Similar persistence has been documented in the European Union and GCC countries, confirming the importance of historical conditions in shaping current food security dynamics (Fusco et al., 2020; Dardeer & Shaheen, 2025). As Mahmud & Banik (2020) note, resilient food systems depend on households' and communities' ability to withstand temporary shocks and maintain stable access to food.

However, sustaining food security over time requires effective environmental management. As shown in Figure 1, environmental quality has a significant negative short-run effect on food security, indicating an ecological trade-off where short-term production gains may come from intensive resource use (Zhuang et al., 2022; Ullah et al., 2018; Lopez-Ridaura et al., 2018). Agricultural intensification, industrial food production, and heavy use of fertilizers and pesticides can increase food availability but may also cause soil degradation, water pollution, and air pollution. Zhuang et al. (2022) and Subramaniam et al. (2019) highlight similar concerns, arguing that environmental degradation can weaken the ecological foundations of food security, especially in developing countries. In the long run, environmental quality becomes statistically insignificant, suggesting that food security depends more on structural resilience, technological progress, and institutional capacity than on short-term environmental changes (Zhuang et al., 2022; Ceesay & Ndiaye, 2022). Improvements in technology, food distribution, and sustainable resource management may reduce some environmental costs of agricultural intensification (Anser et al., 2021; Ullah et al., 2018). Nevertheless, sustainable food security requires environmentally sustainable intensification to avoid accumulating ecological costs over time (Taheri et al., 2017; Akbari et al., 2022).

Water quality is the most consistent environmental factor, with a positive effect on food security in both the short and long run. Clean water supports irrigation, agricultural productivity, ecosystems, and food safety, while pollution from industrial waste, fertilizers, and pesticides threatens food security (UNEP, 2021). This aligns with Affoh et al. (2022) and Allee et al. (2021), who identify water quality as a key foundation of sustainable food systems. Air quality also improves food security in the short run by supporting public health, labor productivity, and crop growth (Sun et al., 2017). Marine water quality has a significant long-run effect, reflecting the importance of healthy marine ecosystems for fisheries, protein supply, and coastal livelihoods (Taylor et al., 2019; Béné et al., 2016).

Agricultural Sector GRDP positively affects food security in both the short and long run by increasing food availability, rural incomes, and investment in infrastructure and innovation (Fusco et al., 2020; Zhuang et al., 2022; Affoh et al., 2022). In contrast, poverty and unemployment reduce food security by limiting access to adequate and nutritious food and weakening households' ability to cope with economic shocks (Gundersen et al., 2021; Akbari et al., 2022; Dessie et al., 2022). Unemployment has a

particularly persistent negative effect because limited income reduces access to sufficient and nutritious food (Broussard, 2019; Smith et al., 2017; Etana & Tolossa, 2017; Abdullah et al., 2017). Evidence from Statistics South Africa also shows that prolonged unemployment increases food shortages, skipped meals, and hunger. Therefore, achieving SDG 2 (Zero Hunger) requires not only higher agricultural productivity but also stronger social protection, job creation, and income security policies (Anser et al., 2021).

CONCLUSION

The Two-Step System GMM results show that food security is highly persistent, meaning that current conditions are strongly influenced by past performance. Environmental quality has a significant negative effect on food security in the short run, reflecting the ecological costs of intensive food production, although its long-run effect is not statistically significant. Specifically, better water, air, and marine ecosystem quality generally support food security by improving agricultural productivity, public health, fisheries sustainability, and ecosystem resilience. Agricultural Sector GRDP strengthens food security in both the short and long run, while poverty and unemployment reduce food security by limiting households' ability to access sufficient and nutritious food. Overall, food security depends not only on production capacity but also on environmental sustainability and socio-economic stability.

These findings suggest that Indonesia should shift from a production-focused approach toward a resilience-oriented food security strategy. First, the government should improve water quality through watershed protection, irrigation rehabilitation, stronger pollution controls, and water-efficient farming technologies. Second, agricultural policies should promote sustainable intensification through precision agriculture, integrated pest management, organic fertilizers, climate-smart farming, and stronger agricultural research and extension services. Third, food security policies should integrate marine conservation, mangrove restoration, sustainable fisheries, and coastal pollution control to improve protein availability and support coastal livelihoods. Fourth, reducing poverty and unemployment requires stronger social protection, rural employment programs, support for smallholder farmers and micro-enterprises, and improved income security. Finally, regional differences require place-based policies rather than a uniform national approach. Areas facing environmental degradation should prioritize ecological restoration and resource efficiency, while regions such as Papua and Maluku need greater investment in infrastructure, market connectivity, food distribution, and public services. Achieving SDG 2 (Zero Hunger) therefore requires an integrated strategy combining environmental protection, agricultural transformation, and social inclusion to build a resilient food system.

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