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Assessing the Role of the Blue Economy in Strengthening Food Security: Evidence from Lower-Middle-Income ASEAN Countries

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Abstract: This study examines the relationship between the blue economy and food security in lower-middle-income ASEAN countries, specifically Indonesia, Cambodia, the Philippines, and Vietnam, over the period 2012–2022. While the blue economy holds significant potential for enhancing food security, its implementation is often hindered by environmental degradation, limited access to renewable energy, inadequate technological advancements, insufficient investment, and rapid population growth. By employing Ordinary Least Squares regression and a system of simultaneous equations, key interactions among environmental quality, renewable energy utilization, technological innovation, investment, and demographic dynamics are analyzed. The findings reveal that improvements in environmental quality foster the adoption of renewable energy, while technological advancements significantly contribute to the expansion of the blue economy. Furthermore, the development of the blue economy is identified as a critical driver of food security, with investment and effective population management playing essential roles in ensuring its long-term sustainability. The results indicate that a comprehensive strategy integrating environmental protection, technological progress, and renewable energy adoption is essential for enhancing food security through the blue economy. Based on these insights, policy recommendations are proposed, emphasizing the need for stringent emission controls, increased investment in renewable energy, promotion of technological innovation, and sustainable demographic policies. These measures are expected to facilitate a resilient blue economy, ensuring food security and long-term socio-economic stability in ASEAN's lower-middle-income nations.

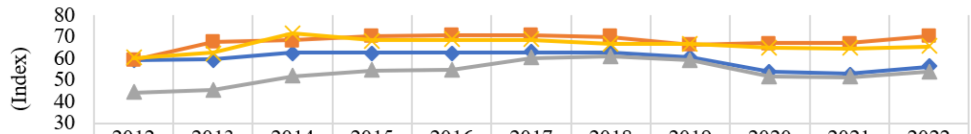
Keywords: Blue economy; Food security; Sustainable development; Environmental quality; Renewable energy; Technological innovation; Investment; Population management

1. Introduction

1.1 Significance of the Topic

In recent decades, the concept of the blue economy has emerged as a key pillar in efforts to achieve sustainable economic growth by utilizing marine resources more efficiently. The blue economy refers to a development strategy that optimizes the sustainable use of marine resources to enhance economic well-being, create jobs, and protect marine ecosystems. As the global population continues to grow and food demand rises, the blue economy has gained recognition as a potential solution to various development challenges, particularly in coastal regions and island nations that heavily depend on marine resources. Numerous studies indicate that marine-based economic sectors—including fisheries, aquaculture, coastal tourism, and marine renewable energy—play a crucial role in supporting food security and sustainable development in many countries.

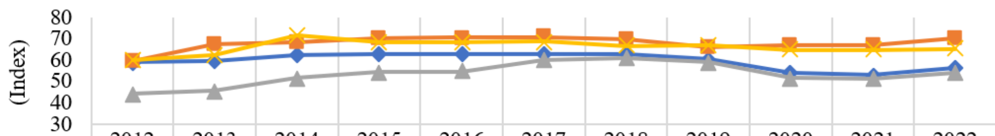
Food security remains a pressing and complex issue, particularly for developing countries in the ASEAN region, which face challenges such as climate change, resource exploitation, and rapid population growth. Food security is determined not only by food availability but also by accessibility, utilization, and supply stability. In this context, the sustainable utilization of marine resources through the blue economy can contribute to food security by providing a reliable protein source through the fisheries sector, supporting economic diversification, and promoting more sustainable production mechanisms. However, countries such as Indonesia, Vietnam, the Philippines, and Cambodia face numerous challenges in effectively implementing the blue economy due to environmental degradation, overfishing, and limitations in technology and investment. Despite the blue economy's significant potential to enhance food security, its implementation continues to encounter various obstacles. Environmental degradation caused by overexploitation, pollution, and the impacts of climate change remains a major barrier to the sustainable use of marine resources. Additionally, rapid population growth in some ASEAN countries places further pressure on food systems and marine resources. Lower-middle-income countries also struggle with limited access to modern technology and the investment needed to develop the blue economy sustainably. Therefore, understanding the relationship between the blue economy and food security, as well as identifying the factors that influence the implementation of blue economy strategies in these countries, is essential. Overall, among the lower-middle-income economies, some countries show more stable and high blue economy performance, while some other countries also face greater challenges in maintaining sustainable maritime economic growth as shown in Figure 1.



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Indonesia	59.1	59.4	62.5	62.6	62.6	62.7	62.8	60.5	53.9	52.9	56.2
Viet Nam	59.3	67.6	68.2	70.1	70.5	70.8	69.8	66.0	67.1	67.1	70.2
Cambodia	44.2	45.5	51.7	54.3	54.6	60.2	61.0	58.9	51.5	51.3	54.0
Philipines	60.1	62.5	71.5	68.4	68.5	68.6	66.7	66.8	64.8	64.6	65.3

Figure 1. Growth conditions of the blue economy in lower-middle-income ASEAN economies

Figure 1 shows the growth of the blue economy in Indonesia, Vietnam, Cambodia, and the Philippines from 2012 to 2022. Vietnam has the highest value, increasing from 59.3 in 2012 to a peak of 70.8 in 2017 and 2018, before rising again to 70.2 in 2022 after a slight decline. The Philippines also recorded a significant increase, reaching 71.5 in 2014, but later experienced declines and fluctuations, settling at 65.3 in 2022. Indonesia tends to remain stable, peaking at 62.8 in 2018 before declining to 53.9 in 2020 and then recovering to 56.2 in 2022. Cambodia, despite having the lowest score, showed improvement, reaching 61.0 in 2018, but dropped back to 54.0 in 2022. Overall, Vietnam and the Philippines exhibit more stability compared to Indonesia and Cambodia. Next, an equally important issue is food security, a major concern for developing countries, particularly lower-middle-income economies in ASEAN. Food security is linked to a country's ability to provide sufficient, affordable, and high-quality food for its entire population. In the context of the blue economy, food security is especially critical for countries with long coastlines that depend on marine resources as a primary component of their national diet. Overall, countries exhibit different patterns in food security development. Despite progress in certain phases, challenges remain, particularly amid global uncertainties that impact economic stability and food production in lower-middle-income ASEAN countries. This phenomenon is illustrated in Figure 2 below.



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Indonesia	59	59	63	63	63	63	63	61	54	53	56
Viet Nam	59	68	68	70	71	71	70	66	67	67	70
Cambodia	44	46	52	54	55	60	61	59	52	51	54
Philipines	60	63	72	68	69	69	67	67	65	65	65

Figure 2. State of food security in ASEAN lower-middle-income economies

Figure 2 shows that from 2012 to 2022, food security in the four lower-middle-income ASEAN countries shows different trends. Indonesia rose from 59 to 63 between 2012 and 2015, then fell to 53 in 2021, and improved slightly to 56 in 2022. Vietnam increased from 59 to 71 from 2012 to 2017, declined to 66 in 2020, and improved back to 70 in 2022. Cambodia improved from 44 in 2012 to 61 in 2018 but fell back to 54 in 2022. The Philippines started at 60 in 2012, peaked at 72 in 2014, and stabilized at 65 from 2019 to 2022. The overall trend shows significant fluctuations in food security in each country. While the blue economy offers great potential to increase the productivity of fisheries, coastal tourism, and ocean-based renewable energy sectors, its implementation in lower-middle-income countries is often met with significant challenges. These countries experience major problems with environmental quality, limited renewable energy, lack of advanced technology, minimal investment, and rapid population growth, all of which contribute to the complexity of achieving sustainable food security.

The state of a country's blue economy is closely linked to the impact of various shocks on other macroeconomic indicators. The blue economy, which involves the sustainable management and utilization of marine resources, is often affected by fluctuations in macroeconomic variables such as economic growth, inflation, exchange rates, and investment levels. Several researchers have conducted in-depth analyses on this subject. For example, the condition of a country's blue economy is influenced by environmental quality. Studies have found that poor environmental conditions, such as pollution and ecosystem degradation, significantly hinder the progress of the blue economy. Healthy marine ecosystems play a crucial role in supporting various blue economy sectors, including fisheries, tourism, renewable energy, and sustainable economic development (Aimon et al., 2021; Bose, 2022; Ebarvia, 2016; Eikeset et al., 2018; World Ocean Initiative, 2020; Karimi et al., 2025; Kathijotes, 2013). Furthermore, renewable energy contributes significantly to the blue economy, particularly through electricity access, which is a key factor in enhancing productivity within blue economy sectors. Findings from various studies (Hakim et al., 2025; Hammar et al., 2012; Pires Manso et al., 2023; Yates et al., 2015; Young, 2015) highlight the critical role of renewable energy in supporting the blue economy by providing a clean and sustainable source of electricity. This transition helps improve the productivity of the marine sector, reduces dependence on fossil fuels, and mitigates negative impacts on marine environments. This aligns with the findings of (Aimon et al., 2023; Kurniadi et al., 2024), which emphasizes that renewable energy sources, such as solar power, serve as essential pillars in reducing the negative effects of climate change caused by fossil fuel consumption, particularly coal. Their study indicates that shifting from coal to solar energy can effectively mitigate climate change, supporting efforts to maintain environmental quality within the blue economy. Additionally, technology plays a vital role in the blue economy (Kurniadi et al., 2024; Samad & Abbasi, 2022; Vedachalam et al., 2019). Technological advancements significantly enhance the management and productivity of the marine sector. Innovations such as advanced monitoring systems, underwater sensors, and data-driven technologies help improve operational efficiency, minimize environmental impacts, and promote the sustainability of marine ecosystems. Investment is another key factor influencing the blue economy (Appiah et al., 2023). Research findings indicate that investment plays a critical role in economic and blue economy development in maritime nations by providing capital for infrastructure, technology, and resource management. Furthermore, studies by Ebarvia (2016) and Spalding (2016) suggest that investment in the blue economy sector significantly contributes to marine sustainability. This includes infrastructure development, technological advancements, and sustainable economic activities that help preserve the quality of marine ecosystems.

1.2 Research Problem

The problem formulation in this study is as follows: what is the relationship between the blue economy and food security in lower-middle-income ASEAN countries (Indonesia, Vietnam, the Philippines, and Cambodia) when influenced by endogenous variables such as environmental quality, renewable energy, technology, investment, and population? This study focuses on lower-middle-income countries in ASEAN—specifically Indonesia, Vietnam, the Philippines, and Cambodia—to explore how the blue economy contributes to food security. The specific objectives of this research are to: (1) analyze the contribution of the blue economy to food security in these countries, (2) identify key challenges in implementing a sustainable blue economy, (3) examine the interaction of environmental variables such as environmental quality, technology, investment, and population growth in influencing the relationship between the blue economy and food security, and (4) provide policy recommendations to enhance the sustainable implementation of the blue economy in support of food security in ASEAN. Through this approach, this research is expected to make a significant contribution to the existing literature while also offering practical insights for policymakers and industry players in addressing the complex challenges faced by lower-middle-income ASEAN countries. The blue economy and food security are closely interconnected, particularly in countries that rely heavily on the fisheries sector and marine resources as primary components of their national food systems. Sustainable fisheries management can enhance food availability, while economic diversification through maritime sectors such as tourism and renewable energy can generate employment and increase income for coastal communities, ultimately improving food access. However, macroeconomic factors such as inflation, exchange rates, and investment policies also influence this relationship. Poor environmental quality, marine pollution, and unregulated resource exploitation can hinder the growth of the blue economy and pose long-term threats to food security. Therefore, this study aims to provide both scientific contributions and policy recommendations for governments and stakeholders to optimize the blue economy as a strategy for enhancing food security in ASEAN.

1.3 Research Objectives

The urgency of this research is to examine and evaluate how exogenous factors such as environmental quality, renewable energy, technology, investment, and population influence the relationship between the blue economy and food security in lower-middle-income ASEAN countries. With rapid population growth and increasing environmental threats, it is crucial to identify strategies that maximize the benefits of the blue economy while ensuring its stability. This research focuses on analyzing the complex relationship between the blue economy and food security in lower-middle-income ASEAN countries by considering endogenous variables such as environmental quality, renewable energy, technology, investment, and population. It aims to understand how each of these variables, along with their interactions, impacts the development of the blue economy and food security. The study applies theoretical frameworks such as sustainable development theory, which emphasizes the need for a balance between economic growth, environmental sustainability, and social welfare.

2. Literature Review

Research on the blue economy and food security analysis has been conducted by Alsaleh (2023), Belhabib et al. (2015), Funge-Smith & Bennett (2019), Spalding (2016), and Techera (2018) using secondary data analysis from FAO reports and case studies focusing on developing countries in Asia and Africa. Researchers applied quantitative analysis to evaluate the contribution of fisheries to food security and qualitative methods to understand the local policy context. This study found that the blue economy has great potential in supporting food security, especially in coastal areas that depend on marine resources. A subsequent study by Silver et al. (2015) investigated the same issue, incorporating environmental, socio-economic, and ecological determinants. Using case studies from various countries, data were collected through interviews, surveys, and policy analysis. They found that small-scale fisheries play a crucial role in supporting food security, particularly in coastal communities. Furthermore, Béné et al. (2016) and Teh & Sumaila (2013) employed simultaneous analysis methods to evaluate the contribution of the fisheries sector to global food security and employment. Econometric models were used to analyze data from multiple countries simultaneously, focusing on the impact of the blue economy on food security and the economies of coastal communities. Their findings indicated that small-scale fisheries significantly contribute to global food security, especially in developing countries, and that policies supporting the blue economy can enhance socio-economic welfare by increasing employment opportunities and food availability. Similarly, Bell et al. (2018) used a simultaneous analysis approach integrating climate, economic, and fisheries data to assess the impact of climate change on small-scale fisheries and food security in the Western and Central Pacific. Simulation models were employed to quantify the effects of climate change on fisheries production and its implications for food security. Their study found that climate change poses a threat to food security in regions dependent on small-scale fisheries.

However, blue economy policies that focus on adaptation and mitigation can help reduce these impacts and enhance food security in vulnerable regions. Furthermore, a study conducted by Barange et al. (2014) and Kurniadi et al. (2024) utilized climate and ecosystem models to assess the impacts of climate change on fisheries production and food security. This research integrates ecological data and climate scenarios to predict changes in ocean productivity and their effects on food security in fisheries-dependent communities. The findings indicate that climate change may reduce ocean productivity, thereby negatively affecting food security, particularly in developing countries. The model provides insights into how adaptation and mitigation strategies can help minimize these adverse effects within the framework of the blue economy. Additionally, a study by Leleu et al. (2012) employed marine habitat mapping techniques using sonar and videography to evaluate the benefits of marine protected areas (MPAs) for marine ecology and fisheries management. The study found that well-managed MPAs can enhance food security by preserving critical fish habitats that support small-scale fisheries. Habitat mapping plays a crucial role in the planning and management of a sustainable blue economy.

Based on explanations from various relevant studies, the novelty of this research lies in several aspects. First, it incorporates a more diverse set of determinant variables, including environmental quality, renewable energy, technology, investment, and population—factors that have not been comprehensively explored in previous studies on the blue economy and food security. While prior research generally focuses on environmental, socioeconomic, and climate change factors, it does not explicitly consider the simultaneous interactions among these variables. Second, this study specifically examines lower-middle-income ASEAN countries, a region that has not been extensively studied in the context of the blue economy and food security. Most prior studies have focused more on Asia and Africa in general or on specific countries. Finally, while simultaneous analysis has been used in previous studies, its application in this research is novel due to the selected combination of variables and its focus on lower-middle-income ASEAN countries. Prior research has typically employed this method to evaluate the impact of a single or limited set of factors, such as climate change or socioeconomic conditions.

3. Methodology

3.1 Data and Variables

This study uses panel data, with the time series covering the period from 2012 to 2022 and the cross-section consisting of lower-middle-income economies in ASEAN, namely Indonesia, Cambodia, the Philippines, and Vietnam. The selection of the 2012–2022 period in this study is based on the relevance of policies, the dynamics of the blue economy, and food security challenges in ASEAN. The year 2012 marks the early adoption of blue economy strategies in many ASEAN countries, aligning with global initiatives such as the Sustainable Development Goals (SDGs), particularly SDG 14, which focuses on the sustainable use of marine resources. This period also reflects significant changes in food security driven by population growth, marine resource exploitation, and the impacts of climate change. Additionally, it encompasses global crises such as the COVID-19 pandemic (2020–2022), which significantly disrupted food supply chains and the blue economy sector. By incorporating data up to 2022, this study can evaluate how the blue economy adapted to external shocks and its role in maintaining food security. Lastly, the availability of reliable data from international institutions such as the World Bank and FAO ensures a more accurate and representative analysis of the relationship between the blue economy and food security in ASEAN. Furthermore, the study categorizes the variables into two types: endogenous and exogenous. The variables classified as endogenous are the blue economy and food security. Meanwhile, the exogenous variables include environmental quality, carbon emissions, renewable energy, investment, and population. The relationships between these variables are summarized in Figure 3.

Based on Figure 3, the indicators for each of the variables used are described in Table 1.

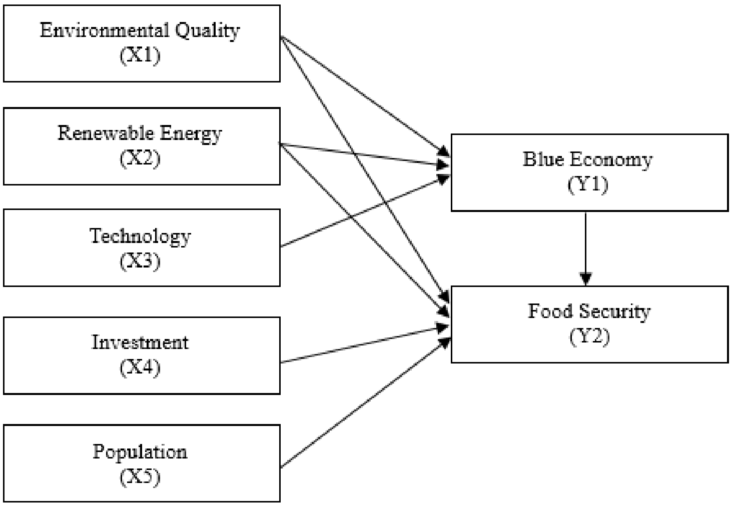


Figure 3. Relationship between variables

Table 1. The variable of research

Variable	Indicator	Source
Blue economy (Y1)	The total marine fisheries production, measured in metric tons, in the ASEAN group of lower-middle-income economies during the period 2012 to 2022.	World Bank
Food security (Y2)	The food security index, measured as an index, in the lower-middle-income economies of ASEAN during the period 2012 to 2022.	Impact Economies
Environmental quality (X1)	Total carbon emissions per capita, measured in metric tons, in the lower-middle-income economies of ASEAN during the period 2012 to 2022.	World Bank
Renewable energy (X2)	Renewable electricity output, measured as a percentage of total electricity output, in the lower-middle-income economies of ASEAN during the period 2012 to 2022.	World Bank
Technology (X3)	Patent applications, measured in total numbers, in the lower-middle-income economies of ASEAN during the period 2012 to 2022.	World Bank
Investment (X4)	Gross fixed capital formation, measured as a percentage of Gross Domestic Product (GDP), in the lower-middle-income economies of ASEAN during the period 2012 to 2022.	World Bank
Population (X5)	Population growth, measured in percentage terms, in the lower-middle-income economies of ASEAN during the period 2012 to 2022.	World Bank

3.2 Data Analysis Model

This study employs the Ordinary Least Squares (OLS) model for Eq. (1) and the simultaneous equation model for Eq. (2). The OLS model was chosen because it is simple, efficient, and provides unbiased and consistent parameter estimates when classical assumptions are met. This model is used to analyze the relationship between the blue economy and food security, as well as the impact of exogenous variables—such as environmental quality, carbon emissions, renewable energy, investment, and population—on the endogenous variables in this study. OLS was chosen because it provides optimal BLUE (Best Linear Unbiased Estimator) estimates, is easy to interpret, and is well-suited for the panel data used in this study. The OLS model's validation is performed through classical assumption tests, including normality, heteroskedasticity, and multicollinearity tests—to ensure it meets the necessary statistical requirements for producing valid and reliable estimates.

The structural equations of the simultaneous equation model in this study are given in Eqs. (1) and (2).

$$Y1it = \alpha 0 + \alpha 1\ X1it + \alpha 2\ X2it + \alpha 3\ X3it + \varepsilon 1it \qquad (1)$$

$$Y2it = \beta 0 + \beta 1\ Y1it + \beta 2\ X1it + \beta 3\ X2it + \beta 4\ X4it + \beta 5\ X5it + \varepsilon 2it \qquad (2)$$

where, α and β: parameter; i: cross section; t: time series; ε: error term.

The next step after determining the structural equation form of the simultaneous equation model is to test its identification using the order condition. There are three possible outcomes for simultaneous equation model identification: not identified, correctly identified, or over-identified. If the test results indicate that the model is over-identified, the analysis is conducted using the two-stage least squares (TSLS) method. Conversely, if the model is correctly identified, the analysis is performed using the indirect least squares (ILS) method. In this study, the identification test confirms that the model is correctly identified, so the analysis is conducted using the ILS method. The application of ILS estimates structural parameters indirectly by leveraging the relationship between the identifying equation and the simultaneously specified variables. In the ILS approach, structural coefficients are obtained through an OLS regression transformation of the exactly identified equation. Based on this method, this study applies a simultaneous equation model using the ILS approach.

4. Results and Discussion

4.1 Blue Economy Analysis

The analysis of the blue economy using the OLS method begins with classical assumption testing before presenting the interpretation of the regression results. The classical assumption tests include normality (Figure 4), heteroskedasticity (Table 2), and multicollinearity (Table 3), which aim to ensure that the regression model meets the criteria of BLUE. The results of these tests are presented first to demonstrate that the model meets the necessary criteria before conducting further analysis of the relationships between variables within the blue economy framework. Consequently, the obtained regression results can be interpreted accurately and without bias.

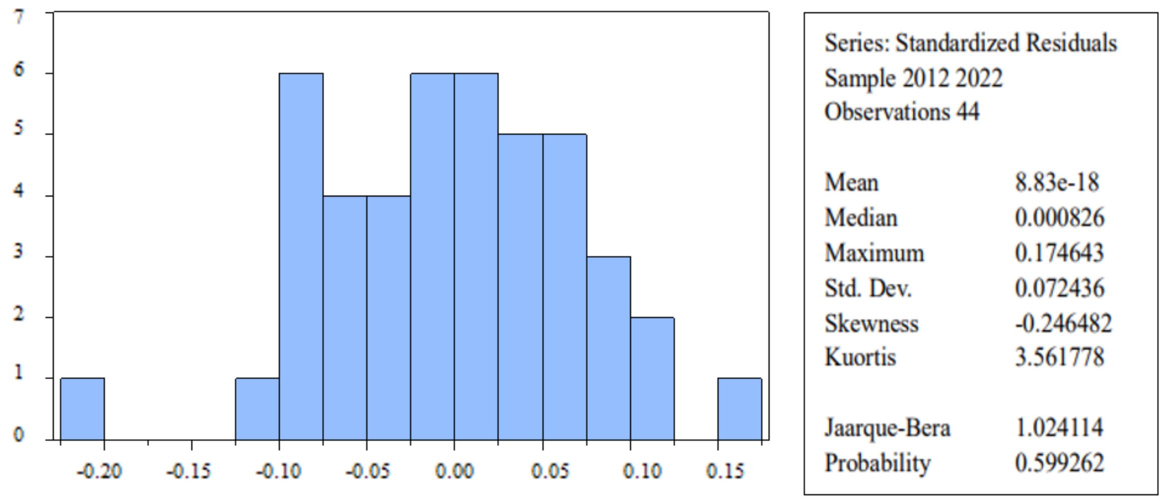


Figure 4. The results of normality test

Table 2. The results of heteroskedasticity test

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.082375	0.045251	1.820402	0.0768
X1	-7.39E-06	1.66E-05	-0.444733	0.6591
X2	0.000248	0.000968	0.256162	0.7992
X3	-0.017495	0.015429	-1.133915	0.2641

Table 3. The results of multicollinearity test

Variable	*X1*	*X2*	*X3*
X1	1.000000	-0.613495	0.531255
X2	-0.613495	1.000000	-0.421505
X3	0.531255	-0.421505	1.000000

The results of the classical normality assumption test, based on the histogram and descriptive statistics in Figure 4, indicate that the residual distribution is relatively close to a normal distribution. The skewness value of -0.264682 suggests a slight leftward skew, while the kurtosis value of 3.361778 is slightly higher than the normal kurtosis value (3), indicating that the residual distribution tends to be leptokurtic. The Jarque-Bera test yields a value of 1.024114 with a probability of 0.599262, which is greater than 0.05. This suggests that there is insufficient evidence to reject the null hypothesis that the residuals are normally distributed. Therefore, the normality assumption in this regression model can be accepted.

The results of the classical heteroskedasticity assumption test, as shown in Table 2, indicate that there is no heteroskedasticity problem in the regression model. This is evidenced by the probability values of each independent variable (*X1*, *X2*, and *X3*), all of which are greater than the significance level of 0.05, indicating no significant relationship between the independent variables and the residual variance. Therefore, it can be concluded that the regression model meets the assumption of homoskedasticity, ensuring that the estimation results are not biased due to non-constant residual variance.

The results of the classical multicollinearity assumption test, as shown in Table 3, indicate that there is no serious multicollinearity issue in the regression model. This is evident from the correlation values among the independent variables, which are below the common threshold of 0.8, suggesting that the relationships between these variables are not excessively strong. Therefore, it can be concluded that the regression model satisfies the assumption of no multicollinearity, ensuring that the regression parameter estimates can be interpreted more reliably.

Once the OLS model satisfies all classical assumption tests, the regression model can be considered an estimator that meets the BLUE criteria. This means that the estimated parameters are linear, unbiased, and have minimum variance. Consequently, the interpretation of the OLS model in blue economy analysis can be conducted with greater validity and reliability. Eq. (3) will illustrate the relationships between the analyzed variables, where the regression coefficients can be interpreted as the effect of independent variables on the dependent variable in the context of the blue economy.

$$Y1it = 2.786^{***} + 0.022\ X1it^{**} + 2.306\ X2it^{*} + 2.674\ X3it^{***} \quad (3)$$

where, ***Significant at $\alpha = 1\%$, ** at $\alpha = 5\%$, * at $\alpha = 10\%$.

Based on the results of the OLS regression estimation, environmental quality (*X1*) and technology (*X3*) are found to have a positive and significant influence on the blue economy (*Y1*). The environmental quality coefficient of 0.022, with a significance level of 1%, indicates that an improvement in environmental quality significantly enhances the blue economy. Similarly, technology exhibits a significant positive influence, with a coefficient of 2.674 at a 1% significance level, confirming that technology adoption and advancement are crucial drivers of blue economy growth. Environmental quality, renewable energy, and technology all play a significant role in shaping the blue economy. High carbon emissions contribute to climate change and ocean acidification, damaging marine ecosystems and threatening key sectors such as fisheries and tourism. The increased use of clean energy sources, such as offshore wind energy, reduces carbon emissions and creates new economic opportunities. Meanwhile, technology, measured through total patents, drives innovation in the management and development of blue economy sectors. Advances in sustainable fisheries, marine energy, and marine environmental monitoring technologies enable more efficient and sustainable resource management. By integrating these three factors, the blue economy can develop sustainably, balancing marine ecosystem preservation with economic productivity.

Environmental quality (*X1*) has been shown to have a significant and positive impact on the blue economy (*Y1*). As carbon emissions decrease, marine ecosystem health improves, which in turn enhances the productivity of key blue economy sectors such as fisheries, tourism, and marine energy. Lower carbon emissions also help mitigate the effects of climate change and ocean acidification, preserving fish populations and biodiversity—both essential for fisheries and nature-based tourism. Studies by (Gattuso et al., 2015) indicate that improved environmental quality supports the recovery of marine ecosystems, directly contributing to the sustainability of the blue economy. Additionally, a cleaner environment enhances the appeal of marine tourism. As highlighted by (Rahman & Mahmud, 2018), maintaining environmental quality leads to increased revenue in the ocean-based tourism sector.

Renewable energy (*X2*) in the blue economy (*Y1*) shows that the relationship between the two follows an inverted U-shaped curve. The inverted U-curve relationship between renewable energy (*X2*) and the blue economy (*Y1*) has significant policy implications for governments and stakeholders. In the early stages of renewable energy adoption, its impact on the blue economy remains positive but insignificant due to high infrastructure costs and technological limitations. Therefore, policies should focus on providing technology incentives and green energy subsidies to accelerate infrastructure development and promote the adoption of more efficient technologies. As renewable energy adoption increases, operational costs decrease, and environmental impacts become more manageable, contributing to blue economy growth. At this stage, policies should encourage public-private investments to expand green energy infrastructure in the maritime sector, such as offshore wind farms and floating solar panels, while also implementing energy efficiency regulations to ensure the optimal use of renewable energy. However, when renewable energy adoption exceeds the optimal point, negative impacts begin to emerge, including land constraints for energy infrastructure, ecosystem disruptions, and rising operational costs due to technology maintenance. Consequently, policies should focus on environmental risk management through zoning regulations and feasibility studies for renewable energy projects to prevent disruptions to coastal ecosystems and fisheries. Additionally, periodic reviews of green energy investment regulations are necessary to avoid excessive expansion that could harm the blue economy. Therefore, the energy transition must be carried out gradually and in a balanced manner to maximize benefits without placing undue pressure on blue economy sectors. Policies should not only promote renewable energy adoption but also anticipate and mitigate the challenges that arise at higher adoption levels. This is due to high infrastructure costs, technological limitations, and a slow transition from conventional energy to renewable energy. A study by Dogan et al. (2020) shows that in the short term, the adoption of renewable energy has not yet had a substantial economic impact due to the suboptimal transition process. As investment in renewable energy increases, its impact on the blue economy becomes more significant, contributing positively to economic growth through reduced carbon emissions and the development of a more environmentally friendly maritime sector. However, after reaching a certain point, this positive impact begins to decline. López-Menéndez et al. (2014) noted that at this stage, although renewable energy contributes positively to economic growth, its impact may diminish after surpassing optimal capacity.

Technology (*X3*), as measured by the total number of patents generated, has a significant and positive impact on the blue economy *(Y1)*. Technological innovation plays a crucial role in enhancing the efficiency and productivity of the blue economy sector (*Y1*). As stated by Dijkstra et al. (2022), technological innovation, as reflected in patent data, plays a key role in driving blue economy growth by increasing productivity and efficiency in the maritime sector through more advanced technological solutions. Additionally, Samad & Abbasi (2022) revealed that technological advancements driven by patent innovation contribute significantly to the development of the blue economy by improving efficiency and sustainability within the maritime sector. Cisneros-Montemayor et al. (2019) also added that the number of patents generated reflects the level of innovation within the maritime sector, which, in turn, positively influences the growth and management of the blue economy. Thus, technology and innovation, as reflected in total patents, play a crucial role in advancing the blue economy and ensuring its sustainability.

4.2 Food Security Analysis

The equation analysis for food security and its influencing determinants is summarised in Eq. (4).

$$Y2it = 0.295^{*} + 1.115\ Y1it^{***} + 0.118\ X1it^{***} + 0.0032\ X2it^{**} + 0.007\ X4it^{**} + 0.363\ X5it^{***} \quad (4)$$

The results of estimating the simultaneous equation using the ILS method show that the blue economy (*Y1*) has a positive and significant effect on food security (*Y2*), with a contribution of 1.115. This confirms the importance of an ocean-based economy in strengthening food security. Environmental quality (*X1*) also contributes positively and significantly, with a coefficient of 0.1181. A healthy environment supports productivity, clean water availability, and biodiversity, all of which are essential for a resilient food system. From an economic perspective, maintaining environmental quality helps reduce costs associated with environmental degradation and productivity losses, ultimately supporting long-term economic stability. This finding indicates that a healthy environment is crucial for sustainable food production.

Renewable energy (*X2*) has a small yet significant positive impact on food security (*Y2*), contributing 0.0032. The use of clean energy reduces dependence on fossil fuels, which are susceptible to price and supply fluctuations. In the economy, the transition to renewable energy can help stabilize food production costs and promote environmentally friendly technological innovations, ultimately benefiting food price stability and consumers' purchasing power. Additionally, integrating renewable energy into agricultural processes can enhance efficiency, reduce greenhouse gas emissions, and improve long-term sustainability. Solar and wind energy, for example, can power irrigation systems and food storage facilities, minimizing post-harvest losses. Lower energy costs from renewables also make food production more affordable, supporting small-scale farmers and local food systems.

Investment (*X4*) has a positive impact of 0.007. Proper investment in infrastructure, technology, and production capacity can enhance efficiency and productivity in food security (*Y2*). Economically, increased investment creates a multiplier effect, stimulating other sectors of the economy and driving overall economic growth. Additionally, investment in modern agricultural practices and supply chain improvements can reduce post-harvest losses and ensure a stable food supply. Enhanced infrastructure, such as better transportation and storage facilities, facilitates market access for farmers, leading to fairer pricing and reduced food waste. Investment in research and innovation also plays a crucial role in developing climate-resilient crops and sustainable farming methods. Moreover, increased capital inflow encourages job creation, improving household income and purchasing power.

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Moreover, developing sustainable food infrastructure is essential for enhancing supply chain efficiency, reducing post-harvest losses, and ensuring equitable food distribution, particularly in rapidly urbanizing regions. Investment in smart logistics, cold storage facilities, and rural transportation networks can help bridge the gap between food production centers and consumers, preventing food shortages in high-density areas. Ultimately, balancing population growth with food security requires a comprehensive, multi-sectoral approach that integrates technological innovation, human capital development, and sustainable resource management. With effective policies in place, population growth can be leveraged as a driver of food security rather than a challenge, ensuring long-term resilience and stability in food systems. However, this growth must be carefully managed to prevent excessive pressure on natural resources and food distribution, which could threaten food security.

The results of this study indicate that the blue economy has a positive and significant influence on food security by ensuring a sustainable supply of animal protein (Alsaleh, 2023). Environmental quality, reflected in carbon emissions per capita, also contributes positively to food security by supporting more sustainable agricultural systems and reducing the negative impacts of climate change. In addition, renewable energy use, measured as the percentage of renewable electricity production per capita, plays a crucial role in food security by reducing dependence on fossil fuels and mitigating environmental impacts that can affect food systems (Zhuang et al., 2022). Investment, measured as a percentage of GDP, supports food security by increasing food production capacity, improving infrastructure, and advancing more efficient technologies. Finally, well-managed population growth contributes positively to food security by ensuring that population increases are matched by adequate food production capacity (Subramaniam & Masron, 2021). Taken together, these factors strengthen food security by enhancing food systems, promoting sustainability, and ensuring efficient resource management.

5. Conclusions

This study highlights the significant impact of environmental quality, renewable energy, and technology on the sustainability of the blue economy and food security in lower-middle-income ASEAN countries. The findings indicate that per capita carbon emissions play a crucial role in marine ecosystem degradation, leading to resource depletion and economic instability in blue economy sectors. Conversely, reducing carbon emissions enhances ecosystem resilience, supports sustainable fisheries, and strengthens food security by ensuring a stable protein supply. Additionally, the study identifies an inverted U-shaped relationship between renewable energy and the blue economy, where early adoption is hindered by high infrastructure costs, technological limitations, and slow energy transitions. However, as investment grows and technology advances, renewable energy increasingly contributes to a more sustainable ocean-based economy. Furthermore, technological progress, measured by the number of patents, positively influences efficiency, productivity, and innovation in key blue economy sectors such as fisheries, aquaculture, and marine energy.

5.1 Policy Recommendations

To enhance the sustainability of the blue economy and food security in lower-middle-income ASEAN countries, several policy measures should be implemented. First, carbon emission control must be prioritized by tightening industrial and maritime emission regulations, implementing carbon pricing mechanisms such as carbon taxes or emission trading systems, and incentivizing industries to adopt low-carbon and energy-efficient technologies. Additionally, regional cooperation on transboundary pollution monitoring and mitigation should be strengthened. Second, the adoption of renewable energy must be accelerated by increasing investments in clean energy infrastructure, such as offshore wind power, floating solar panels, and tidal energy. Providing financial incentives, fostering public-private partnerships, and enhancing grid connectivity can help facilitate the transition from fossil fuels to renewable energy. Third, technological innovation should be encouraged by increasing research and development funding for sustainable fisheries, aquaculture, and marine biotechnology while promoting collaboration between research institutions, industry, and government. Fourth, food security and sustainable fisheries should be strengthened by implementing sustainable fishing practices, improving cold storage and seafood distribution infrastructure, and providing financial support and training to small-scale fishers. Finally, effective population growth management must be pursued through family planning programs, spatial planning policies that balance population growth with marine resource conservation, and sustainable coastal development strategies.

5.2 Future Research Directions

Future research should further explore the findings of this study, which indicate that environmental quality, renewable energy, and technology play crucial roles in the blue economy and food security in lower-middle-income ASEAN countries. Given the inverted U-shaped relationship between renewable energy and the blue economy, future research could investigate optimal clean energy transition strategies to maximize benefits while minimizing economic stress. Additionally, further studies are needed to examine differences in blue economy policy implementation across ASEAN countries, particularly how government regulations and incentives influence the sustainability of the maritime and fisheries sectors. This study also highlights that carbon emissions negatively impact the blue economy, suggesting that future research could assess the effectiveness of carbon taxes or emissions trading mechanisms in supporting marine sector sustainability. Moreover, as climate change and rising sea levels pose increasing threats, further research is needed on adaptation strategies for the fisheries and aquaculture sectors, particularly those based on environmentally friendly technologies. Meanwhile, the development of a circular economy in the marine sector—such as utilizing fisheries waste for bioenergy and managing plastic waste in the ocean—also warrants deeper investigation. Finally, since this study found that technological advancements positively contribute to the blue economy, future research could explore the application of AI, IoT, and blockchain to enhance production efficiency, monitor fish stocks, and improve seafood supply chains. By addressing these aspects, future research can provide more targeted policy recommendations to strengthen a sustainable blue economy and food security in ASEAN.

Author Contributions

S.F. contributed as the lead author of this study, responsible for study design, data collection and analysis, and manuscript writing. H.A. contributed by providing academic guidance and supervision on research methodology and data analysis. Additionally, as the corresponding author, H.A. was also responsible for communication with the journal. A.P.K. contributed by providing academic guidance on research methodology and assisting in the development of policy recommendations based on the study's findings. J.M. contributed by providing guidance, validating theoretical frameworks, and offering critical feedback to refine the research and finalize the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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