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Article

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Material footprint, economic growth, and climate change in emerging Southeast Asian markets

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ABSTRACT

The trade-off between environmental degradation and economic growth is occurring at various global scales due to the use of non-renewable energy. In developed countries, the majority of this issue has been the focus of research and attention. Currently, there is a research gap regarding the material footprint in the relationship between economic development and climate change in emerging markets. This research used a Panel Vector Autoregression (PVAR) model to analyze the causal effects of foreign direct investment, economic development, and material footprint in emerging Southeast Asian economies using Generalized Method of Moments (GMM) regression. This analysis employs five variables, namely the Annual Growth Rate of Real GDP per Capita at Constant 2015 \$ (GDP), Carbon Dioxide Emissions (CDE), Material Footprint (MF), Direct Economic Loss Attributed to Disasters (DEL), and Domestic Material Consumption (DMC). The study's data collection spans from 2000 to 2021. The results of this study provide evidence for the existence of correlations between economic phenomena and climate change in Southeast Asian nations. Material footprints and energy consumption contribute to environmental deterioration. Economic expansion necessitates acknowledging the trade-off that arises from the increased CO₂ emissions released into the environment. A 1% increase in economic growth leads to the release of more than 9% of CO₂ emissions into the environment. Conversely, there is a significant relationship between the amount of environmental pollution and the material footprint. This indicates that the growing consumption of input materials and the inefficient use of these resources are contributing to environmental pollution in rising economies. Natural catastrophes account for more than 3% of the economy's CO₂ emissions. Given the ongoing efforts to lessen the impact of climate change, the study recommends that policy solutions concentrate on restructuring economic growth and improving energy efficiency in industrial operations.

IMPACT STATEMENT

This research supports the government's consideration of implementing a green economy and moving towards sustainable development.

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1. Introduction

Emerging economies confront novel challenges after recovering from the global financial crisis and subsequent economic recovery. Therefore, it is crucial to find a middle ground between the use of resources, the goals of economic expansion, and addressing climate change. The existing methods of economic development in developing countries are inadequate to maintain sustainable growth. Substantial foreign investment and increased material demand drive the fast rise of developing economies in Southeast Asia. Nevertheless, the proliferation and inadvertent repercussions of climate change resulting from the domino effect of fossil fuel use and material imprints are also a source of issue.

Gross Domestic Product (GDP) frequently quantifies economic growth, an indicator of economic development and a fundamental policy objective. In reality, structural development and poverty

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alleviation in countries are contingent upon economic advancement. Nevertheless, increased energy consumption is a consequence of elevated economic activity-induced growth. Environmental degradation may result from increased carbon emissions produced when economic activities become more dependent on nonrenewable energy sources (e.g. coal, petroleum oil, and natural gas) rather than renewable energy. Greater economic growth raises the following inquiry: to what detriment does it come at the expense of ecological health and the environment? In light of escalating globalization, swift climate change, and global warming patterns, this has emerged as a matter of concern for policymakers, governments, and ecologists. As a result, researchers aim to understand the relationship between carbon emissions and economic development through experimental means.

Climate change and economic growth-oriented activities are frequently perceived as two significant interconnected trends. It is anticipated that technological breakthroughs, including artificial intelligence, the Internet of Things, and machine learning, will empower the Fourth Industrial Revolution to fundamentally alter the way in which the world's financial systems, society, and economy function. At present, the trajectory of this metamorphosis is ambiguous; nevertheless, proficient management may yield advantages for both the environment and human society. Conversely, the escalation of greenhouse gas emissions caused by human activities is augmenting the probability of catastrophic climate change events. The Earth is currently experiencing a rapid warming trend, which is expected to surpass the maximum 2 °C target in comparison to the contribution of the industry (Shahbaz et al., 2020).

Lack of access to energy supplies and conversion systems is a constraint on the sustainable development goal of achieving economic benefits without affecting the environment. The environment offers a wide range of renewable and non-renewable energy sources. Increased use of fossil fuels, without action to reduce emissions and waste, will have an impact on global climate change. Energy efficiency and increased use of renewable energy contribute to mitigating climate change and minimizing its consequences for the living environment. The challenge of preserving and safeguarding ecosystems that support the use and advancement of renewable energy sources for economic gains in developing nations and emerging markets requires immediate attention and increased focus. Climate change not only presents a significant threat to human life in developing countries but also creates a substantial barrier for emerging markets. There is a widespread belief that economic activities are the primary contributor to CO₂ emissions and that economic growth is critical for improving human well-being. The Environmental Kuznets Curve (EKC) theory predicts that those with higher incomes and greater environmental education will have greater demands for long-term environmental quality improvement. Enhanced environmental quality contributes positively to both human well-being and economic expansion. The environmental protection mechanism that is considered critical is the EKC hypothesis. Research studies have provided evidence in support of the EKC hypothesis (Nasir et al., 2019; Özokcu & Özdemir, 2017; Pham et al., 2020). It is critical to put the relationship between growth and emissions into a more comprehensive framework, taking into account variations at the national level and additional variables. An analysis of the correlation between emissions and economic growth in developing markets as opposed to developed markets is of critical importance (Bekhet et al., 2017; Charfeddine & Khediri, 2016; Nasir et al., 2019). Finally, it is equally important to consider that a nation's material footprint and levels of material consumption serve as significant catalysts for economic expansion and also play a crucial role in determining carbon emissions, affecting both developed and developing countries (Churchill et al., 2019; Minniti & Venturini, 2017). Developed nations with higher revenues may anticipate greater technological advancements due to their increased investments in technology. These investments may help to implement energy-efficient materials and reduce carbon emissions. By implementing energy efficiency measures, the economy can externalize pollution internalization and appropriate refuse management, thereby mitigating environmental damage and conserving Earth's natural resources. Therefore, it is essential to address ecological challenges, such as biodiversity loss, frequent flooding, and rising temperatures through investments in infrastructure and energy consumption (Churchill et al., 2019).

The economies of Southeast Asian countries have achieved high growth rates in recent years. Southeast Asian countries will have a combined GDP of 3.6 trillion USD in 2022. This will be the fifth-largest economic region in the world. However, the use of non-renewable energy in economic activities has caused huge impacts on environmental pollution. Over the past 25 years, countries in the region have significantly increased their non-renewable energy use. Southeast Asian countries have 8% of the

world's fossil fuel resources. Of these, almost all of Southeast Asian countries' coal reserves are located in Indonesia (83%) and Vietnam (10%). Southeast Asian countries account for 70% of global carbon emissions due to their rapid urbanization and the fourth largest total energy consumption in the world. With the current hot growth rate, the energy supply of Southeast Asian countries is expected to increase steadily from 619 million tons of oil equivalent in 2013 to 1,685 million tons in 2040, with an average annual increase is 4.7%. Southeast Asia is also vulnerable to climate change. The region has one of the world's longest coastlines, making it one of the most vulnerable to global warming and rising sea levels. Southeast Asian countries are facing challenges in developing renewable energy sources and the energy transition process to reduce negative impacts on the environment.

Economic growth at the expense of environmental protection is an issue that developing countries and emerging markets have not paid attention to. Most of these countries consistently prioritize rapid growth over the environmental consequences of their economic activities. Natural disasters caused by climate change and environmental degradation have a significant impact on countries' economies, and the costs associated with addressing and improving these situations are extremely high. Research around the world mainly focuses on selecting samples from developed countries, so the research results are different from those of developing countries. This study contributes to empirical research in four distinct ways. (i) This research investigates the influence of material footprint, energy consumption, and economic development on environmental quality in Southeast Asian emerging markets using an empirical approach and a carbon emission model. (ii) Using the PVAR model through GMM regression without telling the difference between independent and dependent variables allows for a two-way causal relationship analysis between variables, giving a fuller picture of the link between climate change and economic activities. (iii) In contrast to prior investigations on this subject, our study focuses on emerging markets rather than developed ones to conduct experiments (Bekhet et al., 2017; Charfeddine & Khediri, 2016; Nasir et al., 2019). (iv) Additionally, this research employs a sample comprising ten countries rather than concentrating on a single nation. This approach distinguishes it from other studies, as it potentially enhances the effectiveness of efforts to prevent climate change and promote emission reduction trends across multiple countries. The subsequent segment outlines the experimental research and theoretical framework. [Section 3](#) delineates the research model's empirical approach. The research utilizes the PVAR model in conjunction with GMM regression. [Section 4](#) presents and discusses the estimated results. The conclusion follows the points mentioned in [Section 5](#).

2. Empirical studies on the relationship between material footprint, economic growth, energy consumption, and climate change

2.1. Studies on environmental and economic curves

Economic growth's impact on sustainability and climate change policymaking has been the subject of extensive research, expanding from its inception in the Environmental Kuznets Curve (EKC) hypothesis. McKay (2008) examines China's environmental and economic curves. The results demonstrate a correlation between national industrialization, participation in global strategic transformation, levels of non-renewable energy, and environmental pollution. Based on the EKC curve theory and research by McKay (2008), authors can examine China, a world leader in renewable energy consumption, as a country experiencing rapid economic growth and severe environmental consequences. Many studies have paid attention to the issues of material footprint, economic growth, and climate change. Investigations grounded in the EKC hypothesis have yielded varied results. In their research, Onafowora and Owoye (2014) examined time series data from eight countries, including South Korea, China, Brazil, Japan, Egypt, Nigeria, Mexico, and South Africa. The study yielded diverse findings. In the cases of South Korea and Japan, an inverted U-shaped EKC was observed, whereas the remaining six countries reported an inverted N-shaped EKC. Shahbaz et al. (2018) observed that environmental quality in Japan declines with economic expansion. Al-Mulali and Ozturk (2016) discovered in a study of 27 developed economies that, in a similar fashion, environmental quality improves in tandem with economic development, but only over time. Utilizing extensive panel data from 52 emerging economies and 26 OECD countries, Özokcu and Özdemir (2017) found evidence for an inverted N-shaped relationship between environmental degradation and development in the OECD (the emerging economies). Nasir et al. (2019) posit that the

evidence supporting the EKC hypothesis is scant in ASEAN countries. In contrast, Pham et al. (2020) investigated this subject in the context of the European economy, and Shahbaz et al. (2020), utilizing a sample from the United States, present robust evidence in support of the EKC hypothesis.

2.2. Material footprint and sustainable development

Katircioğlu and Taşpınar (2017) and Xu et al. (2018) have shown that energy is considered an important factor in achieving sustainable development. Researchers have conducted extensive research on the correlation between energy consumption and carbon emissions, which in turn influences energy consumption. Renewable energy has experienced a surge in demand over the last several decades, and this trend is continuing. Many subsequent studies also agreed with this view and showed that environmental degradation is mainly the cause of carbon emissions. Additionally, global energy demand for fossil fuels is increasing. Carbon emissions into the atmosphere increase in response to increased consumption of fossil fuels, thereby impacting the environment through the phenomenon of global warming. The principal catalyst for environmental degradation is carbon emissions. While green energy production has the potential to avert future environmental degradation, the transition from fossil fuels to renewable energy can be difficult. Production costs could be one of the obstacles to the transition from fossil fuels to renewable energy. Financial obstacles, such as initial investment, operating expenses, and infrastructure requirements, hinder the production of renewable energy. Various scholars contend that investments in capital and infrastructure are crucial for the production of renewable energy and the prevention of environmental degradation (Destek & Sarkodie, 2019; Sarkodie & Strezov, 2019).

This framework recognizes the need for adequate investment capital to provide financing services, effectively manage risks, and maintain liquidity. Increased investment capital leads to enhanced environmental quality and the promotion of environmentally beneficial projects, creating favorable conditions for investing in clean technology, supporting environmental projects, and reducing emissions, such as those in renewable energy projects. Furthermore, it contributes to improving economic activity efficacy by reducing financial expenses and capital hazards. Stimulating foreign direct investment flows, banking activities, and stock markets bolsters research and development endeavors and investments in sustainable technology (Baloch & Suad, 2018). Other studies also agree with the argument and clarify that the flow of foreign investment into a country can also affect other areas, such as improving infrastructure and technology. The influence extends to environmental degradation and carbon emissions. Using data from the United States from 1970 to 2015, Zafar et al. (2019) examined the effect of natural resource abundance, labor capital, and FDI on the ecological footprint in the context of energy consumption and economic growth. The study used the Zivot-Andrews unit root method to examine the data series' stationarity and structural breaks. Additionally, the Autoregressive Distributed Lag (ARDL) model was utilized to calculate the short-term and long-term elasticities among variables. The results of the study revealed a negative correlation between energy consumption, economic growth, and ecological footprint. Both labor capital and natural resources are highly advantageous in reducing the ecological footprint, in addition to foreign direct investment. In their study, Liu and Kim (2018) investigated the application of vector autoregression to a dataset comprising 44 member countries from 1990 to 2016. The goal was to empirically evaluate the environmental impact of this proposal. The outcomes were assessed in both immediate and delayed scenarios using Impulse Response Functions. This study demonstrates significant variability across a range of target variables, with FDI emerging as the primary variable of interest. Notably, there is no reciprocal relationship between FDI and Ecological Footprint; instead, Ecological Footprint significantly influences FDI alone. Furthermore, this study validates the Pollution Haven Hypothesis concerning FDI and GDP in BRI countries.

2.3. Material footprint, economic growth, and climate change

To ascertain Turkey's participation in global emissions and carbon mitigation, Udemba (2020) employs ecological footprint and foreign direct investment (FDI) activities as surrogates for the environment and foreign investment, respectively. To determine the significance of environmental activities in Turkey, structural break analysis, distributed lag autoregression testing, and Granger causality relationships were utilized. Economic efficacy (per capita GDP) and ecological footprint are found to be positively

correlated, confirming that growth is the cause of pollution. Furthermore, a correlation is found between energy consumption, foreign economic activities (FDI), and ecological footprint, suggesting that both energy consumption and FDI contribute positively to adverse environmental impacts on ecosystems. This provides support for the Pollution Haven Hypothesis, which serves as a fundamental theory in this research. The study includes as one of its findings the Granger causality method, which provides support for the Pollution Haven Hypothesis.

From 1994 to 2017, Usman et al. (2020) examined the causal connections among ecological footprint, foreign direct investment, primary and renewable energy use, trade openness, and economic growth in 33 Upper-Middle-Income Countries (UMICs) spanning Africa, Asia, Europe, and the Americas. For Asia and Europe, the results validate the correlations between economic growth and ecological footprint; for Africa and Asia, foreign direct investment and ecological footprint; for the Americas, renewable energy use and ecological footprint; and for Asia and the Americas, trade openness and ecological footprint. To optimize policy outcomes, it is crucial to establish a correlation between economic expansion, environmentally sustainable technology, and clean energy. This can be accomplished by augmenting the proportion of renewable energy sources in the Americas while fostering economic expansion in Africa and Europe. In addition, policymakers in Asia must prioritize trade liberalization and foreign direct investment while addressing environmental degradation through the use of renewable energy. Further investments in environmental quality should be made by the central agencies of UMICs via trade policies, such as tax exemptions, preferential taxation, and subsidies, as well as through the exchange of renewable energy technology in lieu of foreign direct investment. It is imperative that the governments of these nations modernize their conventional capital to provide a cleaner environment and ultimately enhance human existence. The findings indicate a negative correlation between economic growth and ecological footprint in Europe and Africa; utilization of renewable energy sources in Asia, Europe, and the Americas; and trade liberalization in Asia. Moreover, the findings suggest that trade openness has a detrimental effect on the ecological footprint in both Africa and the Americas. Additionally, the results of the non-causal D-H panel test support the pollution haven hypothesis.

In their investigation of climate change mitigation, Udemba (2021) utilizes a country-specific approach (UAE). The author examined carbon neutrality in the UAE using annual data from 1980 to 2018 to suggest mitigation strategies for climate change. In addition to energy use and population, both linear and non-linear (squared) foreign direct investment (FDI) and per capita GDP were incorporated into the study as focal variables. The inverted U-shaped relationship between economic growth (per capita GDP) and ecological footprint, the positive correlation between energy consumption and ecological footprint, and the negative correlation between foreign direct investment and ecological footprint across all time periods are among the findings of this study. A positive correlation between population and ecological footprint was established, as well as a linear relationship model. The results obtained from the causality analysis indicate that there is a bidirectional or two-way causal relationship in both the short and long term between energy use, urban population, and economic growth (GDP). Additionally, it is important to note that unidirectional transmission occurs in both the short- and long-term, where ecological footprint and FDI influence population; similarly, FDI and energy use are impacted by economic growth; and ecological footprint influences FDI and energy use in the short-term.

Tabash et al. (2023) used the Fully Modified Ordinary Least Squares (FMOLS) model to evaluate data from six GCC nations between 2001 and 2019. According to the statistical findings, economic growth, foreign investment, energy dependence, human capital, and hydrocarbon rent all directly affect CO₂ emissions. On the other hand, foreign direct investment and trade liberalization have an indirect impact on CO₂ emissions. In contrast, the empirical analysis in the GCC country group disproves the Environmental Kuznets Curve (EKC) theory. For linear relationships, the experimental results pertaining to the fundamental premises of the EKC model are statistically insignificant. The GCC region maintains a resolute position regarding carbon dioxide (CO₂) emissions owing to its heavy reliance on primary energy sources, including gas and oil. Environmental economists and other policymakers are provided with policy recommendations regarding environmental sustainability based on current analysis. It is anticipated that the implementation of modern technology and the reduction of fossil fuel dependence will serve as policy instruments that mitigate the adverse externalities associated with numerous economic factors. In the same way that foreign direct investment and trade liberalization tend to reduce

CO₂ emissions, future research should concentrate on these topics. In an innovative manner, the present study examines additional factors pertaining to CO₂ emissions in the GCC region while evaluating the EKC model. Xu et al. (2022) made an estimate of the study's results using data from the WDI and ecological footprint networks from 1990 to 2017 and techniques like FMOLS, DOLS, CCR, and spectral Granger causality. The results of an exhaustive analysis indicate that technological advancement hinders the long-term development of ecological footprints. Meanwhile, the outcomes are considered negligible in the immediate and intermediate futures. Additionally, the utilization of renewable energy and natural resources reduces the ecological footprint over time. On the contrary, the findings indicate that foreign direct investment (FDI) exerts a favorable influence on the ecological footprint level, specifically in China.

Ssali et al. (2019) examines the correlation between foreign direct investment, environmental degradation, economic growth, and energy consumption in six Sub-Saharan African nations from 1980 to 2014. The empirical findings confirm the existence of two-way causal relationships between energy use and CO₂ in the short term and a one-way causal relationship from energy use to CO₂ in the long term. This was proven with panel unit root tests (CADF and CIPS, cross-section independent tests), panel cointegration tests (Pedroni and Kao cointegration tests, panel PP, panel ADF), Hausman panel merger tests, and autoregressive distributed lag modeling. In the long run, there is a strong and unidirectional causal connection between CO₂ and foreign direct investment. However, in the short term, there is no causal association. A 49% increase in CO₂ emissions results from a 1% increase in energy consumption. When economic growth increases by 1%, CO₂ emissions increase by 16%. On the other hand, when economic growth declines by 46%, CO₂ emissions decrease by the square of that increase.

Kızılgöl and Öndes (2022) did a full study of how economic growth, trade openness, urbanization, foreign direct investment, renewable energy use, and natural resource rent affect the environmental impact of 31 OECD countries. Furthermore, the research examines the accuracy of the Environmental Kuznets Curve hypothesis from 1995 to 2017 by using second-generation panel data techniques that account for cross-country interdependence. The results of our study confirm the validity of the inverted U-shaped Environmental Kuznets Curve in OECD nations. In accordance with the findings of the long-term model, it can be seen that urbanization and GDP have a positive impact on the ecological footprint, but other factors have a negative effect. Based on the findings of the causality tests, it can be concluded that there are reciprocal causal connections among the ecological footprint, economic growth, natural resource rent, and trade openness. Furthermore, it can be inferred that there exists a unidirectional causal connection between the progress of urbanization, the use of renewable energy, foreign direct investment, and the ecological footprint.

Ahmad et al. (2020) examine the correlation between natural resources, technical advancement, economic expansion, and ecological impact in developing nations. The conclusions of this research were examined using second-generation panel cointegration techniques, with data spanning from 1984 to 2016. The findings from Pesaran's CD test and the P&Y slope homogeneity test provide empirical evidence supporting the presence of slope heterogeneity among nations and the correlation across cross-sectional units. Furthermore, the results of the cointegration analysis show that there is a long-lasting and consistent link between ecological footprint, natural resources, technological progress, and economic growth. Over time, the expansion of the ecological footprint leads to a rise in natural resources and economic development. However, technological innovation plays a crucial role in mitigating the environmental deterioration resulting from this phenomenon. Adding the fourth-order factor to the study of economic growth also shows that it has a negative impact on the environment, which proves the existence of the Environmental Kuznets Curve (EKC). Additionally, the use of the Augmented Mean Group (AMG) technique confirms the results of the CS-ARDL analysis. Furthermore, the findings from the Dumitrescu-Hurlin Granger causality test indicate that policies targeting natural resources, technological innovation, and economic development have a substantial impact on the ecological footprint, and conversely, policies targeting other factors also have a major effect on the ecological footprint. The primary results of our study highlight the significance and stress the need for implementing suitable policies aimed at the restoration of natural resources, alongside the advancement of technical innovation, to attain sustainable development objectives.

According to Li and Mayer (2022), the issue of environmental degradation has emerged as a significant problem in the South Asian region. Therefore, it is crucial to develop a comprehensive model that

models the macroeconomic factors influencing environmental quality over the whole of this area. It is widely considered that the environmental quality in South Asia has consistently deteriorated due to the continued dependence on conventional fossil fuels by key nations in the area. Given the circumstances, it is possible to propose that commerce within South Asia might provide advantageous circumstances for the exchange of renewable energy, therefore improving environmental well-being. This research seeks to assess the influence of intra-regional trade integration, transition to renewable energy, economic development, and foreign direct investment flows on the ecological footprint of certain South Asian countries. This research utilizes econometric approaches, which are well-suited for working with cross-sectionally dependent, non-stationary panel data. The results show that to lessen the damage that South Asian countries do to the environment, it is important to focus on promoting trade within the region, making it easier for nations to switch to renewable energy sources, encouraging economic growth, and stopping harmful foreign direct investment flows. In addition, the findings of this study provide support for the Environmental Kuznets Curve theory in the South Asian region, namely in Bangladesh, Sri Lanka, Nepal, and Bhutan. However, the results do not support this hypothesis for India or Pakistan. Furthermore, the idea of pollution havens has been substantiated for both the collective and individual nations in South Asia. Based on the aforementioned results, several measures aimed at improving environmental well-being are suggested.

Recent studies have begun to pay attention to the material footprint in the relationship between economic growth and environmental pollution (Ahmad et al., 2020; Li & Mayer, 2022; Tabash et al., 2023; Udemba, 2020; Usman et al., 2020). To achieve the goal of sustainable economic development, each nation must develop more stringent laws, such as sequestration, emphasize the use of sustainable energy sources, and increase GDP to reduce CO₂ through the use of eco-technology, such as carbon capture, thereby saving lives and maintaining a green environment. Current studies that use samples from developing countries primarily focus on the relationship between economic growth and environmental pollution. However, the most significant factor in the relationship between economic growth and environmental pollution, the material footprint of economic activities, rarely receives mention. Therefore, our research examines the material footprint, economic growth, and climate change in emerging Southeast Asian markets. Placing material footprints in the relationship between economic growth and climate change aims to provide a more comprehensive view and more convincing empirical evidence on sustainable development research in emerging countries.

3. Research methodology and data

3.1. GMM estimation of panel VAR models

The general model of PVAR can be expressed as follows:

$$Y_{i,t} = \tau_i + \sum_{k=1}^m \Phi_{l,k} Y_{i,t-k} + \sum_{j=1}^m \Psi_{l,i} X_{i,t-j} + Y_i + u_{i,t}. \quad (1)$$

In formula (1), $Y_{i,t}$ is the $M \times 1$ vector of M observable variables of section individual i at time point t , $X_{i,t}$ is the $M \times 1$ vector of observable deterministic strictly exogenous variables, $\Phi_{l,k}$, $\Psi_{l,i}$ is the coefficient matrix to be estimated of $M \times M$, τ_i is the unobservable M individual fixed effect matrix of individual i , and $u_{i,t}$ is the random error term.

The coefficient matrix to be estimated of the lag endogenous:

$$Y_{i,t} = \tau_i + \sum_{k=1}^m \Phi_k Y_{i,t-k} + \sum_{j=1}^m \Psi_j X_{i,t-j} + Y_i + u_{i,t}. \quad (2)$$

When $s < t$, $Y_{i,t}$, $X_{i,t}$, are orthogonal to the random error term; that is,

$$E[Y_{i,s}] = E[X_{i,s}] = E[Y_i] = 0, (s < t). \quad (3)$$

PVAR (1) model is as follows:

$$(I_m - \phi L)(Y_{i,t} - Y_i - \delta) = u_{i,t}. \quad (4)$$

The GMM estimation process of formula (4) is as follows:

$$\Delta Y_{i,t} - \delta = \phi(\Delta Y_{i,t-1} - \delta) + \Delta u_{i,t}, (t = 2, 3, \dots, T). \quad (5)$$

Thus, the moment condition is obtained:

$$E\{[\Delta Y_{i,t} - \delta - \phi(\Delta Y_{i,t-1} - \delta)]Q_{i,t}^T\} = 0, (t = 2, 3, \dots, T), \quad (6)$$

Where

$$Q_{i,t}^T = (1, Y_{i,0}^T, Y_{i,1}^T, \dots, Q_{i,t-2}^T)^T.$$

Let

$$\Delta Y_i = (\Delta Y_{i,2}, \dots, \Delta Y_{i,T})^T, \Delta u_i = (\Delta u_{i,2}, \dots, \Delta u_{i,T})^T, \Delta Y_{i-1} = (\Delta Y_{i,1}, \dots, \Delta Y_{i,T-1})^T, \text{ and } R_i = [\Delta Y_{i,-1}, I_{T-1}],$$

$\Lambda = [\phi, \psi], \psi = [I_m - \phi]\delta$, 'stack' T-1 formula (5) to get the following:

$$\Delta Y_i = R_i \Lambda + \Delta u_i, i = 1, 2, \dots, N. \quad (7)$$

Meanwhile, formula (6) multiplies the left tool variable matrix:

$$Q_i = \begin{bmatrix} Q_{i2} & 0 & \dots & 0 \\ 0 & Q_{i3} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & Q_{iT} \end{bmatrix}, \quad (8)$$

$$Q_i \Delta Y = Q_i R_i \Lambda + Q_i \Delta u_i$$

$$\min_{\lambda} \sum_{i=1}^N (Q_i \otimes I_m) \text{Vec}(\Delta Y_i) - (Q_i R_i \otimes I_m) \text{Vec}(\Lambda). \quad (9)$$

Get Λ 's estimate. The following is

$$\Sigma = \begin{bmatrix} 2\Omega & -\Omega & \dots & 0 \\ -\Omega & 2\Omega & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 2\Omega \end{bmatrix}. \quad (10)$$

Moreover, by solving the moment condition equation,

$$E[(\Delta Y_{i,t} - \delta - \phi(\Delta Y_{i,t-1} - \delta)) - 2\Omega] = 0, (t = 2, 3, \dots, T), \quad (11)$$

The covariance matrix Ω of $u_{i,t}$ can be estimated. The above GMM estimation is consistent and obeys the asymptotic normal distribution.

The P-VAR model is implemented on the GMM platform. PVAR is an estimation model that uses the OLS platform. However, to overcome the model's defects, the PVAR method running on the GMM platform is used to ensure the model's stability. The PVAR-GMM model is a panel data model developed from the autoregressive vector model to analyze the effects of shocks in a system of factors with mutual causal effects.

3.2. Description of model variables

The study examines the impact of energy consumption, economic development, and climate change on Southeast Asian emerging markets. The research encompasses five variables, namely the Annual Growth Rate of Real GDP per Capita at Constant 2015 \$ (GDP), Carbon Dioxide Emissions (CDE), Material Footprint (MF), Direct Economic Loss Attributed to Disasters (DEL), and Domestic Material Consumption (DMC). The study tests the causal relationship of foreign investment in infrastructure, physical footprint, energy consumption, economic growth and climate change through variables, including Annual Growth Rate of Real GDP per Capita at Constant 2015 \$ (%); Carbon Dioxide Emissions, Per Unit of Manufacturing Value-Added (kg of CO₂ equivalent per constant 2015 \$); Direct Economic Loss Attributed to Disasters (US Dollar); Material Footprint (metric ton) and Domestic Material Consumption (per capita

Table 1. Variable description and data source.

Variables	Variable description	Unit data	Source
GDP	Annual growth rate of real GDP per capita at constant 2015 \$	%	WB
CDE	Carbon dioxide emissions, per unit of manufacturing value-added	Kg of CO ₂ Equivalent Per Constant 2015 \$)	WB
MF	Material footprint	Metric ton	WB
DEL	Direct economic loss attributed to disasters (US dollar)	Logarit	WB
DMC	Domestic material consumption (per capita metric ton)	Logarit	WB

Table 2. Stationarity test results for data series.

Augmented Dickey–Fuller test statistic	t-Statistic	Prob.*	st difference
Null hypothesis: GDP has a unit root	−2.8128	0.0025	$d = 0$
Null hypothesis: CDE has a unit root	−3.8421	0.0001	$d = 0$
Null hypothesis: MF has a unit root	−3.7676	0.0001	$d = 0$
Null hypothesis: DEL has a unit root	−5.4707	0.0000	$d = 1$
Null hypothesis: DMC has a unit root	−7.6382	0.0000	$d = 1$

Source: Compiled from regression results, Stata17.

“*” represents the index to choose whether the series is stopped or not.

metric ton). Direct Economic Loss Attributed to Disasters and Material Footprint is taken logarithmically to bring it to a normal distribution, suitable and responsive to the model's input. It is described in Table 1.

3.2.1. Research data

Direct Economic Loss Attributed to Disasters and Material Footprint is taken logarithmically to bring it to a normal distribution, suitable and responsive to the model's input. Southeast Asia emerging markets include 10 countries: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Myanmar, Thailand, Timor-Leste, Singapore, Malaysia, and Vietnam. The data is obtained from the World Bank (WB) and covers the period from 2000 to 2021. Data is taken from the World Bank (WB): <https://databank.worldbank.org/home.aspx>.

4. Research results and discussion

4.1. Tests of the model

4.1.1. Stationary test for data series

Applying the Dickey–Fuller unit root test method to test for stationarity for the GDP, CDE, MF, DEL, and DMC series. It is described in Table 2.

The results of the Unit Root test indicate that the null hypothesis (H_0) regarding the presence of a unit root is rejected for all series at a significance level of $\alpha = 0.05\%$. This rejection of the H_0 hypothesis leads to the stationary of the GDP, CDE, and MF series, as well as the two series DEL and DMC stop at the first difference level. Consequently, cointegration between the chains is not present because the data series do not converge to the same level of difference. The PVAR model is chosen for regression in accordance with GMM regression.

4.1.2. Optimal lag selection for the model

J , J p -value, MBIC, MAIC, and MQIC are typical criteria that can be applied to ascertain the most suitable latency for the model. MAIC criteria are employed in this instance to ascertain the optimal latency for the model, which is $p = 2$. It is described in Table 3.

4.1.3. Granger causality test

The Granger test assists in ascertaining whether the variables incorporated in the model are exogenous or endogenous, as well as their necessity for inclusion in the model. The model incorporates the following variables when performing the Granger test: GDP, CDE, MF, dDEL, and dDMC. It is described in Table 4.

The findings indicate that the chains GDP, CDE, MF, dDEL, and dDMC form a causal relationship at a significance level of $\alpha = 0.1$. The variables exhibit an interaction relationship, as demonstrated by the

Table 3. Optimal lag selection test results for the model.

Lag	CD	J	J p-value	MBIC	MAIC	MQIC
1	.9998973	98.96863	.0333565	−288.8177	−51.03137	−147.4763
2	.9995022	46.42901	.6174686	−212.0952	−53.57099	−117.8676
3	.9997209	10.48357	.9951325	−118.7785	−39.51643	−71.66474
4	.999954

Source: Compiled from regression results, Stata17.

Table 4. Granger causality test.

Equation/excluded	chi ²	df	Prob > chi ²
GDP			
CDE	0.806	2	0.066
MF	2.045	2	0.036
DDMC	0.355	2	0.083
DDEL	3.978	2	0.013
ALL	7.042	8	0.053
CDE			
GDP	1.099	2	0.057
MF	7.074	2	0.002
DDMC	0.792	2	0.067
DDEL	1.091	2	0.057
ALL	10.110	8	0.025
MF			
GDP	1.140	2	0.056
CDE	0.595	2	0.074
DDMC	2.886	2	0.023
DDEL	2.726	2	0.025
ALL	9.246	8	0.032
DDMC			
GDP	2.659	2	0.026
CDE	0.240	2	0.088
MF	6.412	2	0.004
DDEL	0.007	2	0.099
ALL	11.862	8	0.015
DDEL			
GDP	2.694	2	0.026
CDE	1.192	2	0.055
MF	3.791	2	0.015
DDMC	1.016	2	0.060
ALL	7.884	8	0.044

Source: Compiled from regression results, Stata17.

Table 5. Eigenvalue stability condition test.

Eigenvalue		
Real	Imaginary	Modulus
.9639753	0	.9639753
.8939807	0	.8939807
.7062106	0	.7062106
−.7019874	0	.7019874
−.6180115	0	.6180115
.388065	0	.388065
.2422443	0	.2422443
−.166617	0	.166617
−.145678	0	.145678
.09516	0	.09516

Source: Compiled from regression results, Stata17.

Granger Causality test. Thus, as demonstrated by the aforementioned outcomes, each of the model's components is obligatory.

4.1.4. Model stability test

To evaluate the stability of the PVAR model, verify that all roots or eigenvalues are <1 or fall within the unit circle using the AR Root Test. Stability is then established for the PVAR model. It is described in Table 5.

All the eigenvalues lie inside the unit circle. PVAR satisfies stability conditions.

As a result, the tests demonstrate that the series exhibit stationarity at various levels of difference; consequently, cointegration between the series is ruled out, thereby validating the rationality of selecting the PVAR model. By selecting the appropriate latency as 2, the stability and suitability of the PVAR model for regression are ensured. The author proceeds to perform variance decomposition analysis, using impulse response functions as the foundation for reaching the conclusions.

4.2. Research results and discussion

4.2.1. Impulse response function

The variables Annual Growth Rate of Real GDP per Capita at Constant 2015 \$ (GDP), Domestic Material Consumption (DMC), Material Footprint (MF), Carbon Dioxide Emissions (CDE), and Direct Economic Loss Attributable to Disasters (DEL) are causally influenced by the shocks and fluctuations. The direct economic loss attributed to disasters is substantially impacted by the variability in domestic material consumption and material footprint, as evidenced by the impulse response function. The aforementioned impacts are considerable and statistically significant. This phenomenon can be rationalized by the fact that emerging market economies are developing nations whose economies are highly dependent on substantial quantities of raw materials to sustain their operations. These materials, which are derived from fossil fuels, have a significant negative impact on the environment and contribute to economic damages caused by climate change. Conversely, an enormous amount of influence is exerted on the CO₂ level by means of energy consumption and economic expansion. Consequently, in practice, economic growth rates necessitate an increase in input materials and energy consumption, as well as the acceptance of compromises regarding levels of hazardous emissions. In their pursuit of rapid expansion, emerging markets prioritize economic activities while disregarding environmental and climate change concerns. It is described in Figure 1.

4.2.2. Variance decomposition

The causal relationships among the Annual Growth Rate of Real GDP per Capita at Constant 2015 \$ (GDP), Domestic Material Consumption (DMC), Material Footprint (MF), Carbon Dioxide Emissions (CDE),

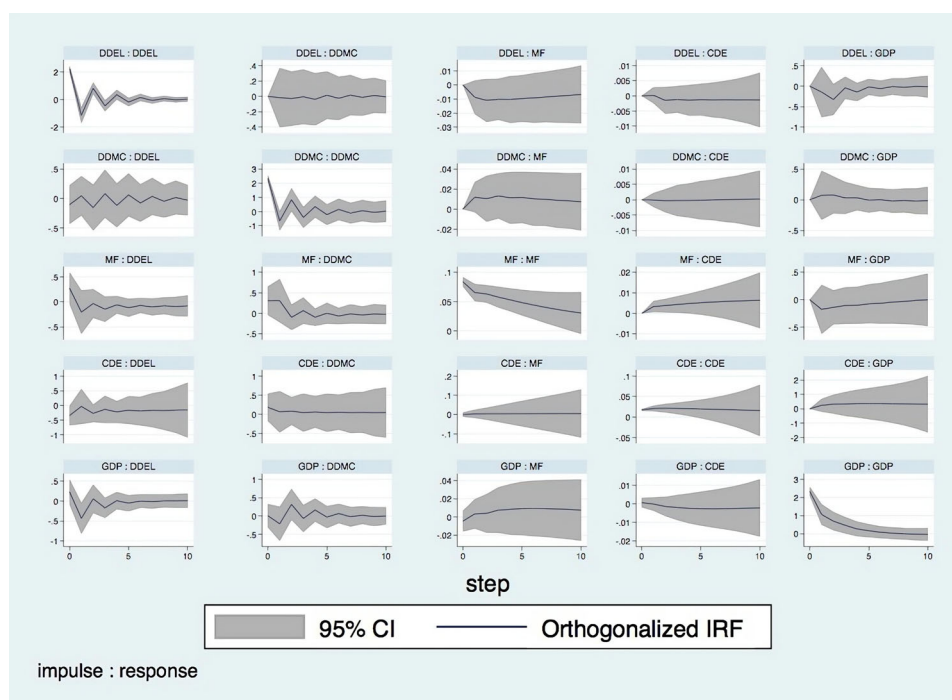


Figure 1. Impulse Response Function of GDP, CDE, MF, DDEL, DDMC.

Note: Describes the response of one variable to the change in the other variables.

and Direct Economic Loss Attributable to Disasters (DEL) are established by the variance decomposition, which yields results consistent with the impulse response function. In contrast to succeeding periods, the impact direction continues to expand. As shown by the fact that a 1% rise in economic growth leads to an environmental CO₂ emissions trade-off of over 9% starting in the eighth period and not decreasing after that, the results suggest that economic growth comes with a big cost. Emerging markets that have limited material resources utilize input materials inefficiently, resulting in increased emissions and environmental degradation, as the material footprint is strongly correlated with CO₂ emissions. The negative economic effects caused by natural disasters are exacerbated by more than 3%, beginning with the second period and continuing thereafter, as a result of the magnitude of the impact of economic growth. Starting from the fifth period and continuing thereafter, the extent to which CO₂ emissions contribute to the adverse economic effects caused by natural disasters increases by more than 3%. In general, Southeast Asian developing nations must prioritize adaptation to climate change while pursuing economic development objectives. It is described in [Table 6](#).

The research results are similar to previous studies (Ahmad et al., 2020; Li & Mayer, 2022; Tabash et al., 2023; Udemba, 2020; Usman et al., 2020). Developing countries use fossil energy sources in large quantities for economic activities. Therefore, to achieve hot growth milestones, we often have to trade off the consequences of emissions and waste entering the environment, leading to environmental degradation and climate change. The empirical findings of the study appear to support the long-term association between the fundamental variables. In the emerging markets of Southeast Asia, the trade-off between economic objectives and climate change is confirmed, which suggests that short-term economic growth will result in environmental degradation, which will continue to have an adverse effect in the long run.

5. Conclusion

The relationship between economic activities and climate change in the emerging markets of Southeast Asia has been the subject of research within the framework of the fourth industrial revolution and worldwide endeavors to reduce carbon emissions. The research has specifically concentrated on examining the possible influence of economic expansion, material footprint, financial development, and energy consumption on the dynamics of CO₂ emissions and climate change. The fourth industrial revolution has brought about significant changes in socio-economic and financial systems, as well as chances for a future without carbon emissions, thanks to groundbreaking technological developments. Hence, it is important to take into account the compromises between economic endeavors and ecological contamination.

Policy-making processes must prioritize the ecological consequences of economic development in light of the current climate conditions to ensure the sustainability of the natural environment. Southeast Asian nations have experienced a recent surge in economic growth, albeit at a comparatively moderate pace when compared to their historical averages. The examination of previous and forthcoming occurrences, such as the ramifications of the COVID-19 pandemic and a sequence of environmental calamities, alongside prospective economic expansion and policy reactions, presents a diverse array of economic and ecological obstacles. To achieve the goal of a carbon-neutral economy in the future, Southeast Asian nations must cultivate a comprehensive approach to building a pristine environment while simultaneously bolstering economic endeavors. Furthermore, it is essential to prioritize investments in sustainable initiatives and provide conducive circumstances for sustainable consumption. The government should prioritize regulating foreign capital flows into the country, encouraging the development of industries using renewable energy. Simultaneously, the government should implement patronage and preferential policies for industries that not only contribute to economic growth but also do not pollute the environment.

The empirical evidence indicates that the environmental impacts of excessive energy use in Southeast Asian countries are substantial. This emphasizes the significance of energy use, not just in facilitating economic activities but also in its ecological consequences. The aforementioned finding is alarming and suggests that Southeast Asian countries should reevaluate their energy policies in response to the climate catastrophe. The data clearly indicates that the current energy sources have resulted in significant environmental degradation. The government must restructure the economy's sectors to promote the

Table 6. Variance decomposition of GDP, CDE, MF, DDEL, DDMC.

Response variable and forecast					
	Impulse variable				
Horizon	GDP	CDE	MF	DDMC	DDEL
GDP					
1	1	0	0	0	0
2	.9830174	.0085377	.0045859	.0007774	.0030816
3	.9531851	.0214522	.0067261	.0015318	.0171049
4	.9394199	.0345521	.0078748	.001576	.0165771
5	.9208632	.0498231	.0089263	.0016695	.0187178
6	.9063289	.0641941	.0094334	.0016455	.0183982
7	.8915358	.078532	.0097768	.0016175	.0185379
8	.8786063	.0916163	.0098491	.0016521	.0182761
9	.866542	.1038787	.0098206	.0016476	.018111
10	.8557778	.1149293	.0097149	.0016901	.0178879
CDE					
1	.0011621	.9988379	0	0	0
2	.0004976	.9843392	.0151046	9.06e-06	.0000497
3	.0021252	.975064	.0207469	.0000937	.0019702
4	.003992	.9675299	.026163	.000105	.0022102
5	.0061166	.9595987	.031405	.0001081	.0027717
6	.0078155	.9523682	.0367987	.0000993	.0029183
7	.0092479	.945309	.0421955	.0000874	.0031602
8	.0103135	.938666	.0476394	.0000778	.0033033
9	.011114	.9322981	.0530274	.0000742	.0034864
10	.0116731	.9262514	.0583546	.0000774	.0036436
MF					
1	.0028612	1.66e-06	.9971372	0	0
2	.00276	.0013216	.9768503	.0123947	.0066734
3	.0030209	.0022557	.966345	.0158915	.012487
4	.0054466	.0029537	.9542692	.0218839	.0154465
5	.0077567	.003573	.9461744	.0244707	.0180252
6	.0104595	.0041718	.9382178	.0273334	.0198176
7	.0127496	.0047833	.9322807	.028899	.0212874
8	.0148585	.0054262	.9269084	.0303881	.0224188
9	.0165643	.0061025	.9226816	.031325	.0233266
10	.0179996	.0068155	.9189854	.0321478	.0240517
DDMC					
1	8.11e-06	.0058244	.0167979	.9773695	0
2	.0073668	.0059212	.0307627	.9559097	.0000396
3	.020886	.0062444	.0285489	.9441617	.0001591
4	.0210098	.0063232	.0284138	.9440956	.0001576
5	.0241311	.0066739	.029016	.939822	.000357
6	.0240915	.0068494	.0288209	.9398488	.0003894
7	.0245854	.0071988	.0292621	.9384761	.0004776
8	.0245961	.0074226	.0292271	.9382374	.0005168
9	.0246305	.0077315	.0294425	.9376531	.0005425
10	.0246545	.0079584	.0294521	.9373698	.0005653
DDEL					
1	.0101761	.0222889	.0141371	.0020558	.951342
2	.0356870	.017516	.0171335	.0018926	.9277709
3	.0324116	.0253369	.0155095	.0048309	.9219111
4	.0349106	.0267148	.0176819	.0054981	.9151945
5	.0340842	.0322905	.0176824	.0070624	.9088805
6	.0341312	.0351408	.0192148	.0074406	.9040726
7	.0338233	.0394354	.0196566	.0080754	.8990093
8	.0336643	.0424692	.0208087	.0081797	.8948782
9	.0334862	.0459236	.0214130	.0084028	.8907745
10	.0333533	.0487246	.0223492	.0084003	.8871727

Source: Compiled from regression results, Stata17.

expansion of environmentally friendly and sustainable manufacturing. Prevent the occurrence of a scenario where the expansion of non-renewable energy sectors, driven by the need for quick economic progress, leads to substantial negative effects on the environment. The government should implement policies that promote and incentivize research and development of renewable energy sources. Simultaneously, the government has the ability to raise taxes on emissions and environmental waste or cease providing credits to projects that contribute to environmental damage. Therefore, it is imperative to reevaluate energy laws and structures, giving more importance to the use of renewable energy sources to accomplish the objective of a carbon-neutral economy in the next few years.

This research aimed to examine the correlation between material footprint, economic development, and climate change in rising Southeast Asian economies by using the PVAR-GMM model. The study findings have presented more empirical proof of the correlation between material footprint, economic development, and climate change in developing Southeast Asian markets. Nevertheless, the research has been unable to measure the precise level of energy use, contribution to the economy, and environmental impact of individual sectors in the economy due to challenges in acquiring data on renewable and non-renewable energy, as well as the complex structure of energy usage and its effects on different economic sectors. Future research is anticipated to delve further into the connection between material footprint, economic development, and climate change in developing sectors of the economy.

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Author contributions

Substantial contributions to the conception or design of the work: Nga Thi Hang Phan. The acquisition, analysis, or interpretation of data for the work and drafting of the work: Thi Thuy Hang Le. Reviewing it critically for important intellectual content: Nga Thi Hang Phan. Final approval of the version to be published: Thi Thuy Hang Le.

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Data availability statement

Data is taken from the World Bank (WB): <https://databank.worldbank.org/home.aspx>.

We agree to make available data and materials supporting the results or analyses in this paper (according to the attached file).

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