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Technological Innovation, Economic Freedom and Environmental Degradation: New Evidence from Time-Varying Causality Analysis in Viet Nam

Nguyen Thi Quy[1,2]*, Ha Thi Thieu Dao[3]

[1]University of Economics and Law, VNU – HCM, Vietnam, [2]University of Finance – Marketing, Ho Chi Minh City, Vietnam, [3]Ho Chi Minh Banking University, Ho Chi Minh City, Vietnam. *Email: quynt22702@sdh.uel.edu.vn

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ABSTRACT

Environmental degradation is one of the most serious issues in recent decades, making studying its impact on the economy imperative. Using a novel time-varying Granger causality approach, we examine the causal relationships between real GDP per capita, technological innovation, economic freedom, and trade openness about environmental degradation (measured through carbon dioxide emissions) in Vietnam from 1990 to 2023. The results indicate a significant causal relationship between technological innovation and the control variable of real GDP per capita to emissions throughout the study period. The direct causal relationship between economic freedom and emissions is minimal; however, when economic freedom is combined with technological innovation, a clear causal relationship with emissions emerges. These findings suggest that investment in green technology can improve the state of environmental degradation in Vietnam. Additionally, economic freedom will transfer green technology from developed countries to Vietnam, contributing to a better environment. On the other hand, ensuring that the growth process is linked to sustainable increases in macroeconomic factors is essential to mitigate the adverse effects of real GDP per capita on the environment.

Keywords: Technological innovation, economic freedom, environmental degradation**,** time-varying causality, Viet Nam.
JEL Classifications: F43, Q55, Q58

1. INTRODUCTION

Environmental degradation has transcended national boundaries to become a pressing global challenge. Mujtaba et al. (2021) argue that the decline in environmental quality is mainly attributable to climate change, driven by rising global temperatures. Environmental economists widely contend that this warming trend is predominantly fueled by greenhouse gas emissions, which threaten the sustainability of human civilization. Among these, carbon dioxide (CO_2) emissions stand out as a primary driver of global warming, constituting a significant proportion of total greenhouse gas outputs (Nkongolo et al., 2008; Chen et al., 2018; Baby et al., 2011; Guy and Levine, 2001; Shu et al., 2010This assessment is endorsed by the Intergovernmental Panel on Climate Change (IPCC) and World Bank (2017). It identifies CO_2 as the dominant contributor to greenhouse gases, with emissions exhibiting a rapidly rising trend over the past two decades—closely related to climate change (ADB, 2013).

For over 79% of greenhouse gas emissions, CO_2 remains a critical environmental impact indicator. Vietnam has the fastest growth rate of greenhouse gas emissions in the world. Vietnam has the fastest growth rate of greenhouse gas emissions in the world. Parallel to the GDP per capita of Vietnam went up from 390 USD to 2000 USD between 2000 and 2015, per capita emissions also more than quadrupled (WB, 2022), which is a typical proof. With ambitious plans of becoming a modern, high-income economy by 2045, economic activities in Vietnam have been continuously expanding. These economic activities are fueled by economic freedom, leading to a surge in production demands, higher energy consumption (especially coal), and over-exploitation of natural resources (Khaliq and Mamkhezri, 2023). As a result, environmental quality has been severely influenced. From this perspective, economic freedom may speed up environmental degradation. Nevertheless, economic freedom encourages market efficiency and competitiveness, allowing more efficient and less resource usage (Bektur, 2023).

On the other hand, environmental degradation can be mitigated by applying advancements in science and technology to promote environmentally friendly economic and production activities, enhancing energy efficiency (Chien et al., 2021; Sharma et al., 2021; Obobisa et al., 2022). Therefore, examining the impact of economic freedom and technological innovation on the environment—measured through CO_2 emissions in Vietnam—is essential.

Although many studies have explored the relationship between economic freedom, technological innovation, and the environment, a comprehensive study has not yet been done in Vietnam. On the other hand, economic freedom may mitigate the influence of technological innovation on environmental degradation (Sakariyahu et al., 2023). Therefore, it is crucial to include an interaction variable between technological innovation and economic freedom to examine the comprehensive impact of these two factors on environmental outcomes.

This study aims to explore the causal linkages among economic freedom, technological innovation and CO_2 emissions in Vietnam while considering other relevant economic factors. By investigating this causal association, the study contributes to and enriches the extant empirical literature on the environment. Furthermore, the research findings are expected to provide robust policy recommendations to enhance environmental quality and achieve sustainable development goals in Vietnam.

This study is separated into five sections. The following section (Section 2) exhibits the theoretical framework and previous empirical studies on the relationship between technological innovation, economic freedom, and CO_2 emissions. In Section 3, the authors present the model, data, and research methodology. The findings of the study are discussed in Section 4. Finally, Section 5 concludes the study through several policy implications and limitations.

2. LITERATURE REVIEW

2.1. Theoretical Background

The Stochastic Impacts by Regression on Population, Affluence, and Technology model (STIRPAT) and the Environmental Kuznets Curve hypothesis (EKC) are two prominent frameworks applied to clarify the complex interrelationships among environmental factors, technological advancements, levels of affluence, energy consumption, population dynamics, and other influential variables.

The STIRPAT model elucidates the interaction among the three most critical pillars of the economy: Technology, affluence, and population about the environment. Dietz and Rosa (1994) were the first to utilize the STIRPAT model to quantify the connection between the environment, population, affluence, and technology by transforming the IPAT model of Ehrlich and Holdren (1971) into a stochastic framework. This transformation enables the identification of environmental changes over time resulting from population growth, technological advancements, and economic expansion. Following the pivotal study by Dietz and Rosa (1994), subsequent research has employed alternative variables to conceptualize technological development, economic prosperity, and population size. Various common indicators have been utilized to measure technological innovation, such as research and development activities, efficiency and patent development (Chen and Lee, 2020), renewable energy (Dong et al., 2018), and energy efficiency (Bargaoui et al., 2014). Similarly, urbanization (Poumanyvong and Kaneko, 2010), population (Dong et al., 2018), and total urban population (Liddle, 2013) are employed to conceptualize the population variable. Economic growth is often employed as a substitute for affluence.

The EKC illustrates an inverted U-shape, referring to the fact that environmental degradation tends to rise in the early stages of economic growth. However, upon accomplishing a certain threshold, environmental degradation is expected to improve (Grossman and Krueger, 1991; Stern, 2004). Although this curve has primarily been utilized for research on the relationship between economic growth and the environment, several studies have also applied it to examine the environment in conjunction with other socioeconomic conditions, such as energy consumption, information and communication technology, tourism development, and institutional issues (Apergis and Ozturk, 2015; Zhang et al., 2017; Islam et al., 2023; Usman and Jahangir, 2021). Consequently, the EKC theory is a foundational framework for describing the association between technological innovation, economic freedom, and environmental quality.

2.2. Empirical Evidence

2.2.1. Technological innovation and environmental degradation

Technological change is necessary to address persistent and worldwide environmental degradation (Weitzman, 1997). Technological innovation is considered a fundamental strategy for reducing CO_2 emissions and battling climate change (Mizobuchi, 2008; Ang, 2009; Okushima and Tamura, 2010), which plays a vital role in environmental conservation (Mizobuchi, 2008; Ang, 2009; Okushima and Tamura, 2010). It is considered a crucial mechanism for alleviating environmental pressures and reducing emissions (Okushima and Tamura, 2010; Álvarez-Herranz et al., 2017; Balsalobre-Lorente et al., 2018; Li et al., 2021).

The effect of technological innovation on the environment, particularly concerning emissions, remains uncertain (Schumpeter, 1949). On the one hand, technological innovation can boost environmental quality; on the other hand, it may accelerate environmental pollution, deteriorating environmental quality. Technological advancements play a vital role in protecting environmental attributes by improving eco-friendly technologies, referred to as regulatory measures that prevent waste disposal into ecosystems (Nathaniel et al., 2021), concentrating on the "Reduce, Reuse, Recycle" (3R) principles. Conversely, technological innovations can indirectly promote the environment by enhancing energy efficiency (Wang and Wang, 2020). Noticeably, technological advancements, especially in green environmental protection technologies, contribute significantly to emissions cuts in OECD countries through energy transitions, particularly the phasing out of harmful energy sources like fossil fuels (Hashmi and Alam, 2019).

Moreover, as Nawab et al. (2021) corroborated, technological innovation promotes the transition to renewable energy and assists in expanding renewable electricity generation capacity in ASEAN countries. Technological innovation is known as a key to sustainability. It offers practical tools and innovative solutions to reduce and reverse environmental degradation, and environmental regulations are essential in promoting these innovations. Similarly, Irandoust (2016) found that innovation significantly improved environmental quality when he investigated the relationship between technological innovation (as represented by R&D expenditures) and environmental pollution in four Nordic countries. Fethi and Rahuma (2019) examined the top 20 refined petroleum oil-exporting countries and discovered that effectively boosting R&D activities related to ecological innovation lowers CO_2 emissions. Khan et al. (2020) identified a long-run negative association between tech innovation and CO_2 emissions in G7 countries.

Nevertheless, several studies indicate that while technological innovation considerably affects environmental quality, it can have adverse effects (Afshan and Yaqoob, 2022; Sun et al., 2021). Adebayo and Kirikkaleli's (2021) study in Japan revealed how technological innovation could trigger CO_2 emissions and contribute to environmental degradation. Similarly, Islam et al. (2023) stated that a negative shock to technological innovation could lead to increased CO_2 emissions. Furthermore, Su et al. (2021), utilising quarterly data in Brazil from 1990 to 2018, confirmed that technological innovation could raise CO_2 emissions. Ahmad et al. (2020) suggested that innovation and foreign direct investment act as the primary drivers of CO_2 emissions in 24 OECD countries. Consequently, the influence of technological innovation on the environment varies across countries due to different innovation proxies and variations in economic growth, financial sectors, and other activities (Janoskova and Kral, 2019).

2.2.2. Economic freedom and environmental degradation

Economic freedom refers to the individual's right to compete, trade, exchange, and transfer property through lawful means. Its core components include individual choice, the protection of private property, and free trade. Economic freedom also encompasses the individual's rights to produce, distribute, and consume goods and services. According to a report by the Fraser Institute, economic freedom comprises five factors: "size of government, legal system and property rights, sound money, freedom of international trade, and regulation" (Gwartney et al., 2021). The extent of economic freedom in a country is often associated with its economic and social objectives, including environmental quality, development levels, and income levels. This relationship is built because economic freedom is referred to as a catalyst that can enhance national growth and development through the introduction and implementation of policies that foster efficient resource utilization in a competitive environment (Wood and Herzog, 2014; Dogan et al., 2021). Carlsson and Lundstrom (2001) asserted that economic freedom could influence the environment directly or indirectly via different channels, comprising institutional quality, market efficiency, and macroeconomic policy stability. The environment will have a good chance of making progress in reducing pollution if appropriate laws are enacted and enforced to constrain polluting activities. Furthermore, macroeconomic stability (i.e. stable macroeconomic conditions and policies) can also support economic growth, investment, and consumption. However, increased output due to heightened demand can drive more substantial environmental pollution, enforcing the implementation of effective management policies and regulations to control pollution.

Additionally, a competitive market is expected to foster the development of new and more efficient production and service delivery methods, ultimately resulting in lower prices, that can be facilitated through technology transfer from developed to developing countries (Gallagher and Thacker, 2008; Tchamyou and Asongu, 2017). Economic freedom can indirectly improve environmental degradation by enabling countries to access cleaner and more energy-efficient technologies (Amoah et al., 2020).

Economic freedom exerts a direct influence on environmental degradation through multiple channels. Asongu (2018) presumes that adequate environmental protection is enclosed with economic freedom, which relies on three core dimensions: accountability, transparency, and information accessibility. Nonetheless, rising income levels in G-20 countries, which stimulate heightened demand for goods and services, have been proven to weaken environmental quality (Alola et al., 2022). Key economic freedom indicators such as trade openness, regulatory frameworks, legal systems, monetary stability, and property rights play an important role in interceding effects, impacting economic outcomes (Does economic freedom affect green economic growth? Analyses of mediation, moderation, and heterogeneity in EU and non-EU countries, 2025).

By contrast, Awad (2022) proves that robust political institutions are fostered by effective governance, citizen empowerment to leverage political rights and a free press. This heightened oversight allows more efficacious monitoring of natural resource usage, promoting improvements in environmental outcomes.

3. DATA AND METHODOLOGY

3.1. Data

This study empirically analyzes the time-varying causal relationship between technological innovation (TI), economic freedom (EF), real GDP per capita (RPCGDP), and CO_2 emissions (CO_2) in Vietnam. Annual data were converted into monthly time series using a widely recognized interpolation method to expand the number of observations in the dataset (Hung et al., 2022). As a result, 384 observations, a suitable timeframe for this study, were realized. The time series data for Vietnam from 1991 to 2022 were obtained from the World Development Indicators (World Bank, 2023) except for TI, which was sourced from the OECD website, and EF, retrieved from the Heritage.org website. Table 1 will provide detailed information on the indicators by description, unit of measurement, and data source.

3.2. Methodology

This study utilizes the time-varying Granger causality test developed by Shi et al. (2018) to examine the relationship between technological innovation, economic freedom, real GDP per capita, and the interaction between technological innovation, economic freedom, and CO_2 emissions. The lag-augmented VAR (LA-VAR) approach for conducting Granger causality tests (Shi et al., 2018; Shi et al., 2020) is followed by three time-varying causality approaches: the recursive algorithm, the rolling average, and the recursive evolving algorithm. The LA-VAR model is as follows:

$$y_{1t} = \Upsilon_{10} + \Upsilon_{11}t + \sum_{i=1}^{k+d} \rho_{1i}\Upsilon_{1t-i} + \sum_{i=1}^{k+d} \delta_{1i}\Upsilon_{2t-i} + \varepsilon_{1t} \quad (1)$$

Where y_1 represents per capita CO_2 emissions; y_2 represents technology innovation, the degree of economic freedom, real GDP per capita, and the interactive variable; d represents the maximum integrated order for y_t. The null hypothesis of no Granger causality from y_{2t} to y_{1t} is tested using the Wald Test as follows:

$$H_0 = \delta_{11} = \ldots = \delta_{1k} = 0 \quad (2)$$

The time-varying Granger causality test is conducted using subsamples of the data based on the maximum Wald statistic. "The Wald statistic on [f1, f2] is the starting and ending point f_1 and f_2, with the sample size fraction $f_w = f_2 - f_1 \geq f_0$ designated by $W_{f_2}(f_1)$ and represented by.

$$SW_f(f_0) = \frac{sup}{(f_1, f_2) \in \wedge_{0,} f_2 = f}\{W_{f_2}(f_1)\} \quad (3)$$

Where: $\wedge_0 = \{(f_1, f_2): 0 < f_0 + f_1 \leq f_2 \leq 1, \text{ and } 0 \leq f_1 \leq 1 - f_0\}$ for the minimum sample size $f_0 \in (0, 1)$ in regression.

The rules are defined based on the recursive development algorithm for a basic transformation example.

$$\widehat{f_e} = \frac{\inf}{f \in [f_0, 1]}\{f : SW_f(f_0) > scv\} \text{ và } \widehat{f_f}$$
$$= \frac{\inf}{f \in [\widehat{f_e}, 1]}\{f : SW_f(f_0) < scv\} \quad (4)$$

Where $\widehat{f_e}$ and $\widehat{f_f}$ are the first-time-ordered observations with statistical test data, and SW_f is the critical value related to the SW_f statistics.

4. RESULTS AND DISCUSSION

4.1. The Unit Root Test and Optimal Lag

Initially, variable stationarity is verified by utilising Dickey-Fuller (ADF) (Dickey and Fuller, 1979) and Phillips-Perron (PP) (Shi et al., 2018) tests. Test results in Table 2 confirm that the variables are stationary. Accordingly, the d values within the Granger causality analysis remain temporally invariant.

Table 1: Indicators with description, measuring units, and sources

Variables	Description	Measuring units	Data sources
CO_2	CO_2 emissions	Metric tons per capita	WB (2023)
TI	Technological innovation	Patents on environmental technologies	OECD (2023)
EF	Economic freedom	Index	Heritage Foundation
RPCGDP	Real gross domestic products	GDP per capita (constant 2015 US$)	WB (2023)

We conducted a unit root test on all variables to test the causal relationship between CO_2, TI, EF, RPCGDP, and the interaction variable EF×TI. We used traditional unit root tests, including ADF and PP, to account for the stationary properties of the data series. The stationarity test results are shown in Table 3.

Table 3 shows that all other variables are stationary at the root level except for the TI variable, which is stationary at the first difference. Therefore, the variables included in the analysis of the causal relationship over time are appropriate.

Next, the lag of the variables is determined, and the optimal lag is selected based on the AIC information criterion. The results are presented in Table 4.

4.2. Causality Analysis

The Wald test results in Table 5 reveal a Granger causality nexus from technological innovation (TI) at a 1% significance level for the entire sample period. This finding supports the work of Ahmad et al. (2022) and Liang et al. (2022), which confirms that technological innovations, particularly green technologies, positively lessen the mitigation of environmental degradation. Moreover, the time-varying Granger causality between TI and CO_2 emissions is illustrated throughout the sample period in Figures 1(a) and 1(b). These graphs indicate a bidirectional causal linkage between technological innovation and CO_2 emissions. Notably, this causal relationship is evident during various periods, particularly in 2002, 2013, and 2018 for the influence of TI on CO_2 emissions and in 2002 and 2013 for the reverse influence of CO_2 emissions on TI. This finding suggests that whereas technological innovation (especially in green technology) effectively mitigates emissions, increased emissions conversely stimulate the development of more environmentally beneficial technologies.

In Vietnam's economy, advancing environment-related technologies can mitigate harmful energy sources contributing to environmental degradation, promoting energy conservation, particularly non-renewable energy sources such as coal.

Regarding the time-varying Granger causality between economic freedom and CO_2 emissions in Figure 2a and b, the results provide evidence of an unclear causal relationship between

Figure 1: Recursive Expanding Wald Test for Technology innovation Granger causes per capita CO_2 emission and vice versa.

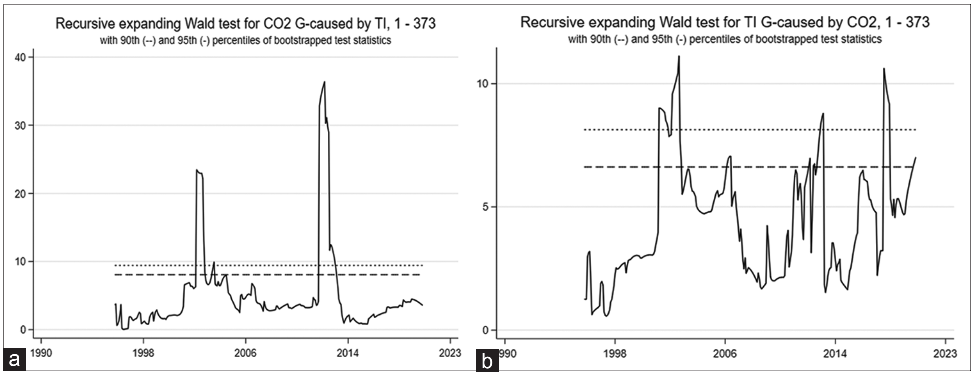


Table 2: Descriptive statistics

Variable	Obs	Mean	Standard deviation	Min	Max	Skewness	Kurtosis
CO_2	385	1.421	0.967	0.308	3.560	0.788	2.474
TI	373	15.512	8.665	2.7	40	0.691	3.258
EF	325	49.274	5.620	38.6	61.7	0.079	2.661
RPCGDP	385	1822.233	861.446	673.386	3655.463	0.493	2.044
EF×TI	313	671.42	297.797	119.61	186.468	0.336	2.805

Table 3: Unit – roots test

Variables	PP		ADF		Order of integration
	Intercept and trend		Intercept and trend		
	Level I (0)	First Diff I (1)	Level I (0)	First Diff I (1)	
CO_2	−5.686	−372.674***	−1.892	−20.063***	I (1)
TI	−23.643**	−369.765***	−3.383*	−19.174**	I (0)
EF	−11.591	−329.545***	−2.447	−18.517 ***	I (1)
RPCGDP	−4.026	−362.335***	−1.783	−21.388***	I (1)
EF×TI	−11.266	−391.332***	−2.376	−19.961***	I (1)

Source: Own calculation with ***, **, *indicate the significance level at 1%, 5%, and 10% respectively

Table 4: Optimal lag length for CO_2, TI, IQ, RPCGDP and EF×TI

Variables	Lag length	
	AIC	BIC
CO_2	1	1
TI	1	1
EF	1	1
RPCGDP	4	1
EF×TI	1	1

Source: Own calculation

Table 5: Wald test result

Causality from	Causality to: CO_2		
	Max Wald FE	Max Wald RO	Max Wald RE
TI	4.739	33.896***	53.841***
	8.057	8.447	8.972
	10.364	10.361	10.918
	15.331	14.836	15.331
EF	7.897	27.526***	29.253***
	5.861	8.102	8.934
	8.605	11.430	11.667
	12.244	15.310	15.532
RPCGDP	6.766	17.687**	13.632**
	7.523	9.023	7.678
	9.680	10.533	10.278
	18.889	19.833	16.175
EF×TI	4.886	34.204***	39.244***
	7.513	8.147	8.607
	9.591	9.472	9.953
	18.549	17.337	18.549

***, **, *indicate the significance level at 1%, 5%, and 10% respectively

economic freedom and emissions throughout the time series and identify a unidirectional causal relationship between emissions and economic freedom. However, the interaction term between economic freedom and technological innovation (EF×TI) exhibits a bidirectional Granger causality with CO_2 emissions during specific years of the study period (Figure 3a and b). Specifically, there is a one-way causality from EF×TI to CO_2 in 2003 and 2013, while a reverse causality is confirmed in 2002, 2013, and 2019. This result aligns with Gallagher and Thacker (2008), Tchamyou and Asongu (2017), Ullah et al. (2020), and Amoah et al. (2020), asserting that economic freedom indirectly affects environmental degradation. In Vietnam's economy, technological innovation related to the environment has the potential to mitigate harmful energy sources that accelerate environmental degradation, thereby contributing to the conservation of energy consumption, particularly non-renewable energy resources such as coal.

Furthermore, a bidirectional causal relationship was also found in the case of the CO_2-RPCGDP pair. The Wald test and the Granger causality diagram in Figure 4a and b encourage the significant connection between real GDP per capita and emissions throughout the time series. Precisely, the study supports a unidirectional causality between RPCGDP and CO_2 from 2000 to 2020.

It implies that rapid growth in real GDP per capita can considerably be associated with increased emissions and thereby aggravate environmental degradation. From another

Figure 2: Recursive Expanding Wald Test for Economic freedom Granger causes per capita CO_2 emission and vice versa.

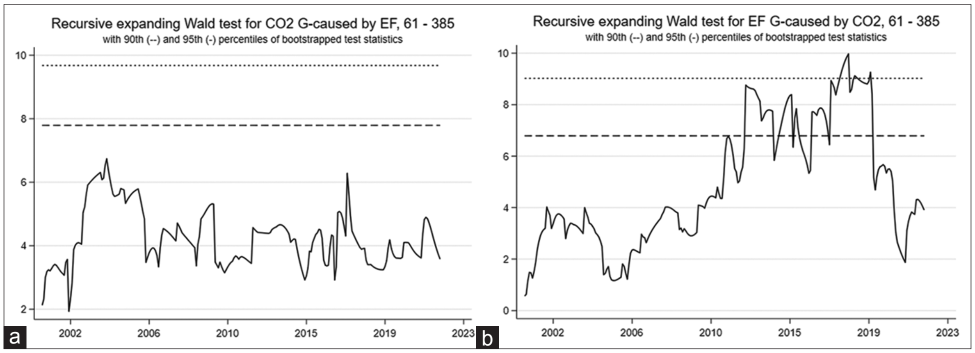


Figure 3: Recursive Expanding Wald Test for the interaction term between Economic freedom and Technological innovation Granger causes per capita CO_2 emission and vice versa.

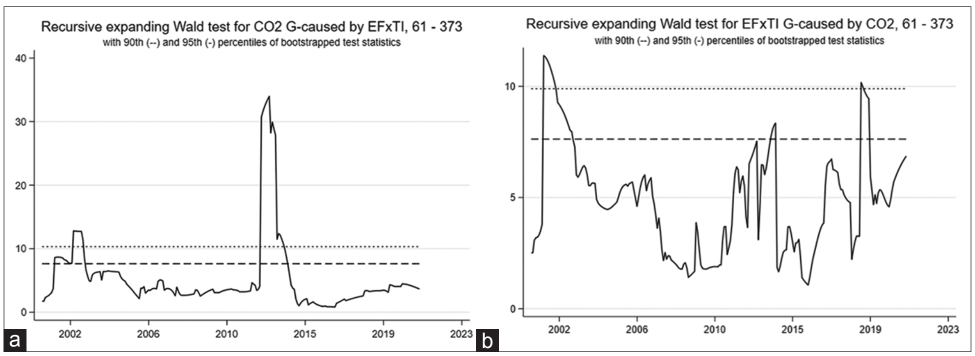
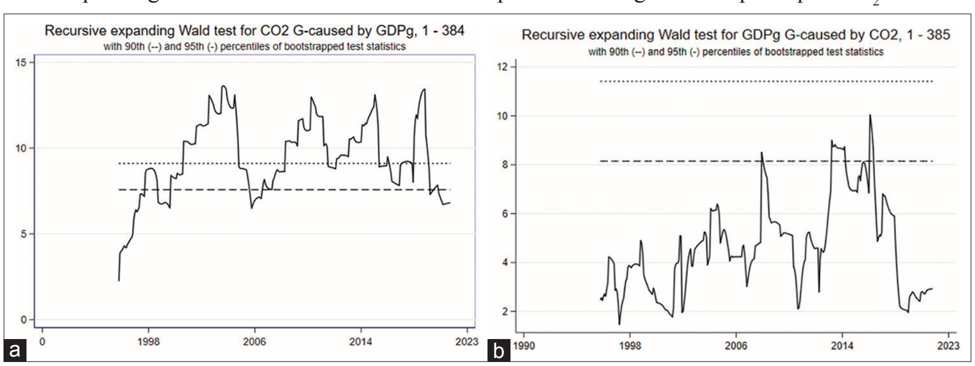


Figure 4: Recursive Expanding Wald Test for real Gross domestic products Granger causes per capita CO_2 emission and vice versa.



perspective, rapid real GDP per capita in Vietnam indeed stimulate large-scale industrialization, thus rising non-renewable energy sources. This process will exhaust natural resources and lead to environmental degradation. Hence, real GDP per capita can forecast emissions, which has crucial implications for policymakers in Vietnam. This result is thoroughly consistent with many previous studies, like Appiah (2018), Nguyen et al. (2024), and Minh et al. (2023).

5. CONCLUSION AND POLICY IMPLICATIONS

Numerous studies have investigated the interplay between technological progress, economic freedom, and macroeconomic variables about CO_2 emissions, with a recent shift in focus from developed economies to emerging markets such as Vietnam. However, within the context of Vietnam's economy, there remains a significant research gap concerning the specific roles of technological innovation and economic freedom, as well as their interactions, particularly when accounting for the influence of economic growth on emissions. The present study comprehensively investigates the direct and indirect effects of technological innovation and economic freedom - adjusted for economic growth - on CO_2 emissions in Vietnam between 1990 and 2023. Utilizing a time-varying Granger causality test, this study evaluates and confirms directional and dynamic relationships of the research variables. A robust causality was identified between technological innovation and CO_2 emissions, particularly concerning relevant environmental technologies. Conversely, the causal effect of CO_2 emissions on technological innovation was most apparent in 2003 and 2013. Within the same timeframe, economic freedom did not reveal a direct causality on emissions, but its influence was mediated via technological innovation.

Meantime, as a control variable, economic growth demonstrated a clear and consistent causal association with emissions. These findings convey vital implications for policymakers seeking to promote sustainable development in Vietnam. The mobilisation of economic resources - primarily external investments - is critical to obtain and enhance advances in technological innovation (especially in green and environmentally friendly technologies). Besides, attempts to adjust and foster trade liberalisation and economic globalisation should be integrated into robust environmental regulations to accelerate the implementation of advanced technologies from developed countries. Concurrently, pursuing economic growth alongside industrialisation requires careful consideration to make it compatible with environmental sustainability. The recommendation can be attained through sustainable resource management, a priority for renewable energy in production systems, and a stringent and cohesive implementation of relevant policies to prevent environmental degradation. Such measures involve expediting green transition creativities in the private sector, extending the scope of goods subject to environmental taxation, and initiating a practical carbon credit trading framework.

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REFERENCES

Afshan, S., Yaqoob, T. (2022), The potency of eco-innovation, natural resource and financial development on ecological footprint: A quantile-ARDL-based evidence from China. Environmental Science and Pollution Research, 29(33), 50675-50685.

Adebayo, T.S., Kirikkaleli, D. (2021), Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: Application of wavelet tools. Environment, Development and Sustainability, 23(11), 16057-16082.

Ahmad, M., Ahmed, Z., Bai, Y., Qiao, G., Popp, J., Oláh, J. (2022), Financial inclusion, technological innovations, and environmental quality: Analyzing the role of green openness. Frontiers in Environmental Science, 10, 851263.

Alola, A.A., Alola, U.V., Akdag, S., Yildirim, H. (2022), The role of economic freedom and clean energy in environmental sustainability: Implication for the G-20 economies. Environmental Science and Pollution Research, 29(24), 36608-36615.

Álvarez-Herránz, A., Balsalobre, D., Cantos, J.M., Shahbaz, M. (2017), Energy innovations-GHG emissions nexus: Fresh empirical evidence from OECD countries. Energy Policy, 101, 90-100.

Amoah, A., Kwablah, E., Korle, K., Offei, D. (2020), Renewable energy consumption in Africa: The role of economic well-being and economic freedom. Energy, Sustainability and Society, 10(1), 32.

Ang, J.B. (2009), CO_2 emissions, research and technology transfer in China. Ecological Economics, 68(10), 2658-2665.

Apergis, N., Ozturk, I. (2015), Testing environmental Kuznets curve hypothesis in Asian countries. Ecological Indicators, 52, 16-22.

Appiah, M.O. (2018), Investigating the multivariate Granger causality between energy consumption, economic growth and CO2 emissions in Ghana. Energy Policy, 112, 198-208.

Asian Development Bank. (2013). Low-Carbon Green Growth in Asia: Policies and Practices. Available from: https://www.adb.org/sites/default/files/publication/159319/adbi-low-carbon-green-growth-asia.pdf

Asongu, S.A. (2018), ICT, openness and CO_2 emissions in Africa. Environmental Science and Pollution Research, 25(10), 9351-9359.

Awad, A. (2022), Is there any impact from ICT on environmental quality in Africa? Evidence from second-generation panel techniques. Environmental Challenges, 7, 100520.

Baby, J., Jini, D., Ajisha, S.U. (2011), Fight global warming with genetically altered trees. Asian Journal of Biotechnology, 3(4), 337-344.

Bektur, C. (2024). The role of economic freedom in achieving the environmental sustainability for the highest economic freedom countries: Testing the environmental Kuznets curve hypothesis. Environmental Science and Pollution Research, 31(60), 67187-67196.

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., Farhani, S. (2018), How economic growth, renewable electricity and natural resources contribute to CO_2 emissions? Energy Policy, 113, 356-367.

Bargaoui, S.A., Liouane, N., Nouri, F.Z. (2014), Environmental impact determinants: An empirical analysis based on the STIRPAT model. Procedia-Social and Behavioral Sciences, 109, 449-458.

Carlsson, F., Lundström, S. (2001), Political and Economic Freedom and the Environment: The case of CO_2 emissions. Working Papers in Economics No. 29. Goteborg: Department of Economics, Goteborg University.

Chen, J., Wang, P., Cui, L., Huang, S., Song, M. (2018), Decomposition and decoupling analysis of CO_2 emissions in OECD. Applied Energy, 231, 937-950.

Chen, Y., Lee, C.C. (2020), Does technological innovation reduce CO_2 emissions? Cross-country evidence. Journal of Cleaner Production, 263, 121550.

Chien, F., Hsu, C.C., Ozturk, I., Sharif, A., Sadiq, M. (2022), The role of renewable energy and urbanization towards greenhouse gas emission in top Asian countries: Evidence from advance panel estimations. Renewable Energy, 186, 207-216.

Dickey, D.A., Fuller, W.A. (1979). Distribution of the estimators for autoregressive time series with a unit root. Journal of the American statistical Association, 74(366a), 427-431.

Dietz, T., Rosa, E.A. (1994), Rethinking the environmental impacts of population, affluence and technology. Human Ecology Review, 1(2), 277-300.

Doğan, B., Driha, O.M., Balsalobre Lorente, D., Shahzad, U. (2021), The mitigating effects of economic complexity and renewable energy on carbon emissions in developed countries. Sustainable Development, 29(1), 1-12.

Dong, K., Hochman, G., Zhang, Y., Sun, R., Li, H., Liao, H. (2018), CO_2 emissions, economic and population growth, and renewable energy: Empirical evidence across regions. Energy Economics, 75, 180-192.

Ehrlich, P.R., Holdren, J.P. (1971), Impact of population growth: Complacency concerning this component of man's predicament is unjustified and counterproductive. Science, 171(3977), 1212-1217.

Fethi, S., Rahuma, A. (2020), The impact of eco-innovation on CO_2 emission reductions: Evidence from selected petroleum companies. Structural Change and Economic Dynamics, 53, 108-115.

Gallagher, K.P., Thacker, S.C. (2008), Democracy, Income, and Environmental Quality. Vol. 1. Weißenhorn: PERI. p34-48.

Grossman, G.M., Krueger, A.B. (1991), Environmental Impacts of a North American Free Trade Agreement. NBER Working Papers No. 3914. National Bureau of Economic Research, Inc.

Guy, E.D., Levine, N.S. (2001), GIS modeling and analysis of Ohio's CO_2 budget: Mitigating CO_2 emissions through reforestation. The Ohio Journal of Science, 101, 34-41.

Gwartney, J., Lawson, R., Hall, J., Murphy, R. (2021), Economic freedom of the world-2021 Annual Report. Institute of Economic Affairs Monographs.

Hashmi, R., Alam, K. (2019), Dynamic relationship among environmental regulation, innovation, CO_2 emissions, population, and economic growth in OECD countries: A panel investigation. Journal of Cleaner Production, 231, 1100-1109.

Heritage Foundation. (2024), Available from: https://www.heritage.org/index

Hung, N.T., Trang, N.T., Thang, N.T. (2022), Quantile relationship between globalization, financial development, economic growth, and carbon emissions: Evidence from Vietnam. Environmental Science and Pollution Research, 29(40), 60098-60116.

Irandoust, M. (2016), The renewable energy-growth nexus with carbon emissions and technological innovation: Evidence from the Nordic countries. Ecological Indicators, 69, 118-125.

Islam, M.S., Rahaman, S.H. (2023), The asymmetric effect of ICT on CO_2 emissions in the context of an EKC framework in GCC countries: The role of energy consumption, energy intensity, trade, and financial development. Environmental Science and Pollution Research, 30(31), 77729-77741.

Janoskova, K., Kral, P. (2019), An in-depth analysis of the summary innovation index in the V4 countries. Journal of Competitiveness, 11(2), 68-83.

Khaliq, A., Mamkhezri, J. (2023), Asymmetrical analysis of economic complexity and economic freedom on environment in South Asia: A NARDL approach. Environmental Science and Pollution Research, 30(38), 89049-89070.

Khan, Z., Ali, S., Umar, M., Kirikkaleli, D., Jiao, Z. (2020), Consumption-based carbon emissions and international trade in G7 countries: The role of environmental innovation and renewable energy. Science of the Total Environment, 730, 138945.

Li, X., Hu, Z., & Zhang, Q. (2021). Environmental regulation, economic policy uncertainty, and green technology innovation. Clean Technologies and Environmental Policy, 23(10), 2975-2988.

Liang, H., Li, G., Zhang, W., Chen, Z. (2022), The impact of green innovation on enterprise performance: The regulatory role of government grants. Sustainability, 14(20), 13550.

Liddle, B. (2013), Population, affluence, and environmental impact across development: Evidence from panel cointegration modeling. Environmental Modelling and Software, 40, 255-266.

Minh, T.B., Ngoc, T.N., Van, H.B. (2023), Relationship between carbon emissions, economic growth, renewable energy consumption, foreign direct investment, and urban population in Vietnam. Heliyon, 9(6), e17544.

Mizobuchi, K. (2008), An empirical study on the rebound effect considering capital costs. Energy Economics, 30(5), 2486-2516.

Mujtaba, A., Jena, P.K., Joshi, D.P.P. (2021), Growth and determinants of CO_2 emissions: Evidence from selected Asian emerging economies. Environmental Science and Pollution Research, 28(29), 39357-39369.

Nathaniel, S.P., Murshed, M., Bassim, M. (2021), The nexus between economic growth, energy use, international trade and ecological footprints: The role of environmental regulations in N11 countries. Energy, Ecology and Environment, 6(6), 496-512.

Nawab, T., Bhatti, M.A., Nawaz, M.A. (2021), Does technological innovation advance environmental sustainability in Asean countries? Pakistan Journal of Humanities and Social Sciences, 9(3), 425-434.

Nguyen, M.Q., Dimou, M., Vu, T.T.H., Schaffar, A., The, C.P., Nguyen, N.Q. (2024), Testing the ecological footprint of economic growth in developing countries. The case of Vietnam. Journal of International Development, 36(5), 2457-2477.

Nkongolo, N.V., Kuramochi, K., Hatano, R. (2008), Effect of mechanized tillage operations on soil physical properties and greenhouse gases fluxes in two agricultural fields. Research Journal of Environmental Sciences, 2(2), 68-80.

Obobisa, E.S., Chen, H., Mensah, I.A. (2022), The impact of green technological innovation and institutional quality on CO_2 emissions in African countries. Technological Forecasting and Social Change, 180, 121670.

Okushima, S., Tamura, M. (2010), What causes the change in energy demand in the economy?: The role of technological change. Energy Economics, 32, S41-S46.

Poumanyvong, P., Kaneko, S. (2010), Does urbanization lead to less energy use and lower CO_2 emissions? A cross-country analysis. Ecological Economics, 70(2), 434-444.

Sakariyahu, R., Lawal, R., Etudaiye-Muhtar, O.F., Ajide, F.M. (2023), Reflections on COP27: How do technological innovations and economic freedom affect environmental quality in Africa? Technological Forecasting and Social Change, 195, 122782.

Sarker, D., Bhattacharya, S., Rodriguez, R.D., Sheremet, E., Kabiraj, D., Avasthi, D.K., Zahn, D.R., Schmidt, H., Srivastava, P., Ghosh, S. (2016), Unraveling the origin of enhanced field emission from irradiated feco-SiO_2 nanocomposites: A combined experimental and first-principles based study. ACS Applied Materials and Interfaces, 8(7), 4994-5001.

Schumpeter, J.A., Hausman, D.M. (1949), Science and Ideology. American Economic Review, 1994, 224-238.

Sharma, G.D., Tiwari, A.K., Erkut, B., Mundi, H.S. (2021), Exploring the nexus between non-renewable and renewable energy consumptions and economic development: Evidence from panel estimations. Renewable and Sustainable Energy Reviews, 146, 111152.

Shu, Y., Lam, N.S., Reams, M. (2010), A new method for estimating carbon dioxide emissions from transportation at fine spatial scales. Environmental Research Letters, 5(4), 044008.

Stern, D.I. (2004), The rise and fall of the environmental Kuznets curve. World Development, 32(8), 1419-1439.

Su, C.W., Xie, Y., Shahab, S., Faisal, C.M.N., Hafeez, M., Qamri, G.M. (2021), Towards achieving sustainable development: Role of technology innovation, technology adoption and CO_2 emission for BRICS. International Journal of Environmental Research and Public Health, 18(1), 277.

Tchamyou, V.S., Asongu, S.A. (2017), Information sharing and financial sector development in Africa. Journal of African Business, 18(1), 24-49.

Usman, M., Jahanger, A. (2021), Heterogeneous effects of remittances and institutional quality in reducing environmental deficit in the presence of EKC hypothesis: A global study with the application of panel quantile regression. Environmental Science and Pollution Research, 28(28), 37292-37310.

Wang, Q., Wang, L. (2020), Renewable energy consumption and economic growth in OECD countries: A nonlinear panel data analysis. Energy, 207, 118200.

Weitzman, M.L. (2017), Sustainability and technical progress. In: The Economics of Sustainability. Oxfordshire: Routledge. p329-341.

World Bank. (2023), Available from: https://data.worldbank.org/country/Vietnam

Wood, J., Herzog, I. (2014), Economic Freedom and Air Quality. Vancouver, Canada: Fraser Institute.

Zhang, B., Wang, B., Wang, Z. (2017), Role of renewable energy and non-renewable energy consumption on EKC: Evidence from Pakistan. Journal of Cleaner Production, 156, 855-864.