Research Article

Can Trade Openness Foster a Greener Future? Evidence from APEC Economies on Macroeconomic Drivers of Environmental Sustainability

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Abstract: This study investigates the dynamic effects of trade openness, income level, renewable energy consumption, and R&D expenditure on environmental degradation in 16 selected Asia-Pacific Economic Cooperation (APEC) member countries over the period 1990–2023. Using total greenhouse gas emissions (GHG) per capita as a comprehensive measure of environmental degradation, the analysis incorporates FDI, industrialization, and urbanization as control variables to account for broader macroeconomic and structural influences. This study employs a robust econometric framework including Prais–Winsten regression, Panel-Corrected Standard Errors (PCSE), Random Effects Generalized Least Squares (RE-GLS), and Robust Least Squares (RLS) estimation models. The empirical results reveal that trade openness has a mitigating effect on greenhouse gas emissions, suggesting that increased trade may promote cleaner technologies and encourage more environmentally friendly production processes within APEC economies. In contrast, income level and industrialization are found to significantly lead to environmental degradation, while renewable energy consumption exhibits a consistent and significant negative relationship with GHG emissions. R&D expenditure highlights the role of innovation in reducing emissions in the RLS estimation, but its effect remains model-dependent. Moreover, Granger causality results conclude the bidirectional relationships between most variables and environmental degradation. These results underscore the importance of integrated policies that promote renewable energy, green industrial strategies, and sustainable trade practices. This study offers empirical insights into environmental governance in the APEC region and contributes to the evolving discourse on balancing economic development with ecological sustainability.

Keywords: Trade Openness, Environmental Sustainability, Greenhouse Gas Emissions, Renewable Energy Consumption, APEC Economies
Jel Codes: Q01, Q56, Q55

Ticaret Açıklığı Daha Yeşil Bir Geleceği Teşvik Edebilir mi? APEC Ekonomilerinden Çevresel Sürdürülebilirliğin Makroekonomik Belirleyicilerine Dair Kanıtlar

Öz: Bu çalışma, 1990–2023 dönemi için seçilmiş 16 Asya-Pasifik Ekonomik İşbirliği (APEC) üyesi ülkede ticari açıklık, gelir düzeyi, yenilenebilir enerji tüketimi ve AR-GE harcamalarının çevresel bozulma üzerindeki dinamik etkilerini incelemektedir. Çevresel bozulmanın kapsamlı bir göstergesi olarak kişi başına toplam sera gazı (GHG) emisyonları kullanılmış, ayrıca daha geniş makroekonomik ve yapısal etkileri dikkate almak amacıyla doğrudan yabancı yatırım (DYY), sanayileşme ve kentleşme kontrol değişkenleri olarak analize dâhil edilmiştir. Çalışmada Prais–Winsten regresyonu, Panel-Corrected Standard Errors (PCSE), Random Effects Generalized Least Squares (RE-GLS) ve Robust Least Squares (RLS) tahmin yöntemlerini içeren güçlü bir ekonometrik çerçeve kullanılmıştır. Ampirik bulgular, ticari açıklığın sera gazı emisyonlarını azaltıcı bir etkisi olduğunu ortaya koymakta; bu da artan ticaretin daha temiz teknolojileri teşvik edebileceğini ve APEC ekonomilerinde daha çevre dostu üretim süreçlerini destekleyebileceğini düşündürmektedir. Buna karşılık, gelir düzeyi ve sanayileşmenin çevresel bozulmayı önemli ölçüde artırdığı, yenilenebilir enerji tüketiminin ise GHG emisyonlarıyla tutarlı ve anlamlı bir şekilde negatif ilişki gösterdiği bulunmuştur. Ar-Ge harcamaları, RLS

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tahmininde emisyonların azaltılmasında yeniliğin rolünü vurgulasa da etkisinin modele bağlı olduğu görülmektedir. Ayrıca Granger nedensellik testleri, çoğu değişken ile çevresel bozulma arasında çift yönlü ilişkiler bulunduğunu ortaya koymaktadır. Bu sonuçlar, yenilenebilir enerjiyi, yeşil sanayi stratejilerini ve sürdürülebilir ticaret uygulamalarını teşvik eden bütüncül politikaların önemini vurgulamaktadır. Çalışma, APEC bölgesinde çevresel yönetişim konusunda ampirik bulgular sunmakta ve ekonomik kalkınma ile ekolojik sürdürülebilirliğin dengelenmesine yönelik gelişen tartışmalara katkıda bulunmaktadır.

Anahtar Kelimeler: Ticaret Açıklığı, Çevresel Sürdürülebilirlik, Sera Gazı Emisyonları, Yenilenebilir Enerji Tüketimi, APEC Ekonomileri
Jel Kodları: Q01, Q56, Q55

1. Introduction

In recent years, balancing sustainable economic growth with environmental preservation has become a critical issue on the global policy agenda. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), global greenhouse gas (GHG) emissions must fall by 43% by 2030 compared to 2019 levels to limit global warming to 1.5°C. Yet, emissions have continued to rise, particularly in fast-developing regions such as the Asia-Pacific. In 2020, APEC (Asia-Pacific Economic Cooperation) economies accounted for approximately 60% of global energy-related CO_2 emissions (IEA, 2022), highlighting the region's critical role in shaping the trajectory of global climate outcomes.

The literature reveals various findings regarding the environmental concern of trade deficit. Similarly, the pollution-haven hypothesis suggests that countries with more open economies might become attractive locations for pollution-heavy industries because of their relatively lax environmental regulations (Cole, 2004; Copeland & Taylor, 2003). Conversely, the technique effect posits that trade can enhance environmental outcomes by enabling access to cleaner technologies and stricter environmental standards (Antweiler et al., 2001). For instance, Managi, Hibiki, & Tsurumi (2009) found that trade openness improves environmental quality in high-income nations but deteriorates it in low-income nations due to institutional disparities.

Similarly, economic expansion has a complex, non-linear relationship with environmental degradation, often described by the Environmental Kuznets Curve (EKC) hypothesis. This framework suggests that as income rises, environmental degradation first intensifies but begins to fall once a specific income level is surpassed (Grossman & Krueger, 1995). However, recent studies challenge the universality of the EKC, especially in emerging economies where industrial expansion and urbanization persist (Shahbaz et al., 2015).

Renewable energy consumption has gained prominence as a sustainable alternative to fossil fuels. Several empirical studies demonstrate its mitigating effect on GHG emissions (Dogan & Seker, 2016; Nathaniel & Iheonu, 2019). Al-mulali et al. (2015) found a significant negative interaction between green energy use and CO_2 emissions in both developed and developing countries. However, the transition toward renewables is often constrained by structural factors such as industrial dependency, investment flows, and urban growth dynamics.

Similarly, foreign direct investment (FDI), industrialization, and urbanization also exert considerable influence on environmental outcomes. While FDI can transfer green technologies, it may also exacerbate pollution in host countries lacking environmental enforcement (Tang & Tan, 2015). Industrialization, particularly in energy-intensive sectors, has been widely linked to higher emissions (Zhang & Cheng, 2009). Urbanization, meanwhile, presents a dual effect, also it may increase emissions through higher consumption and transportation demand, while on the other, it can enable economies of scale in energy use and infrastructure (Poumanyvong & Kaneko, 2010).

In addition, technological progress has become an increasingly important factor in shaping environmental outcomes. Research and development (R&D) expenditure is often viewed as a proxy for innovation capacity, which can either reinforce conventional industrial growth or foster cleaner technologies depending on its orientation (OECD, 2022). While some studies suggest that R&D investment supports environmental sustainability through green innovations, others highlight its potential to intensify emissions when focused on traditional, energy-intensive sectors.

Given this context, this study investigates the dynamic effects of trade openness, income level, renewable energy, and R&D expenditure on environmental degradation, measured by per capita GHG emissions, across 16 selected APEC member economies over the period 1990–2023. By incorporating FDI, industrialization, and urbanization as control variables, the study captures a broader set of macroeconomic and structural drivers that influence environmental quality. The APEC region offers a unique context for this analysis due to its economic diversity, rapid industrial development, and varying degrees of environmental governance. The results are expected to contribute to the ongoing discourse on sustainability and inform policy frameworks aiming to balance growth with ecological responsibility.

This study contributes to empirical literature in several ways. First, while numerous studies have examined the link between economic variables and carbon dioxide (CO_2) emissions, far fewer have focused on total GHG emissions. Compared to the large body of CO_2-based research, the number of studies addressing aggregate GHGs remains limited, although it has been expanding in recent years (Dharmapriya et al., 2025; Zhou, 2025). By incorporating CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6 emissions across multiple sectors, this study captures a more comprehensive spectrum of anthropogenic environmental impacts, consistent with IPCC (2023) standards.

Second, the study focuses on 16 selected APEC member countries from 1990 to 2020, a region that has received limited attention in the environmental economics literature despite its significance in global trade and emissions. The economic diversity of APEC—from highly developed economies like Japan and the United States to emerging economies like Indonesia and the Philippines, offers a valuable opportunity to explore heterogeneous effects across varying institutional and developmental contexts.

Third, the study applies a multi-method econometric framework to address the methodological challenges inherent in panel data analysis, such as cross-sectional dependence, contemporaneous correlation, heteroskedasticity, and unobserved heterogeneity. Specifically, the analysis employs Prais–Winsten regression, Correlated Panels Corrected Standard Errors (PCSEs), Random Effects Generalized Least Squares (RE-GLS), and Robust Least Squares (RLS) estimation techniques. These are supplemented by diagnostic tests, robustness checks, and alternative estimation strategies to ensure the consistency and reliability of results.

The methodological design is tailored to the structural and policy heterogeneity of the APEC region, acknowledging differences in environmental governance, economic maturity, and vulnerability to global shocks. By using multiple estimation techniques and robustness strategies, the study enhances the credibility of its findings and mitigates model-dependence bias—a common limitation in prior research. Finally, the study provides policy-relevant insights into how trade integration, economic modernization, technological progress, and energy transitions interact with environmental sustainability. The results are expected to inform regional and national strategies aiming to balance growth with emission reduction commitments, particularly considering evolving global climate frameworks such as the Paris Agreement.

The study is as follows: Section 2 reviews the literature on the relationship between environmental degradation and key macroeconomic variables. Section 3 describes the dataset, definitions, and methodology. Section 4 presents empirical results. Section 5 presents the discussions, and Section 6 concludes the study by summarizing the key findings and proposing policy recommendations to support sustainable development across APEC member economies.

2. Literature Review

The connectedness between economic activities and environmental degradation, especially in terms of GHG emissions, has been thoroughly studied in the field of environmental economics. Researchers have long debated how various economic factors influence the environment, with a focus on how trade, industrialization, economic growth, energy consumption, and foreign investment contribute to environmental outcomes. One pioneering study in this area is by Grossman & Krueger (1991), who explored the link between economic expansion and environmental degradation through the lens of the EKC. Their work suggested that while industrialization and economic growth initially lead to higher levels of pollution, a turning point could be reached where further economic development results in improved environmental quality, largely due to the adoption of cleaner technologies and stronger environmental policies. A significant portion of this study has focused on the trade-offs between promoting economic growth and maintaining environmental sustainability. As global trade has increased and industrialization has accelerated, the environmental impact of these activities has become a key concern. In this context, literature also examines how policies and technological innovations, such as the adoption of renewable energy, can mitigate these economic drivers. This section reviews the key strands of research relevant to the variables in this study: trade openness, economic expansion, green energy consumption, FDI, industrialization, and urbanization.

2.1 Trade Openness and Environmental Degradation Nexus

There is a growing body of literature examining the interaction between trade openness and environmental outcomes, reflecting diverse theoretical perspectives and empirical evidence. Several studies lend support to the *pollution haven hypothesis*, suggesting that trade liberalization may shift pollution-intensive industries to countries with weaker environmental regulations (Han et al., 2024; Özkan et al., 2024). For instance, Li et al. (2022) analyze the development–environment nexus in 89 BRI countries and find overall support for the EKC hypothesis, with FDI generally improving environmental quality in Europe, though regional disparities persist and evidence for the pollution haven hypothesis remains mixed. Building on this debate, the classical literature emphasizes two contrasting mechanisms: while the *pollution haven hypothesis* (Cole, 2004; Copeland & Taylor, 2003) predicts that open economies may attract pollution-intensive industries, the *technique effect* suggests that trade integration can foster cleaner production through technology transfer and stricter standards (Antweiler et al., 2001). Managi et al. (2009) showed that trade openness improved environmental quality in high-income countries but worsened it in lower-income contexts. More recent studies further extend this debate; Bakri et al. (2025) identify a threshold effect of trade openness on carbon emissions in Asian economies, Zhou (2025) demonstrates that trade liberalization can reduce CO_2 emissions under supportive institutional frameworks, and Dharmapriya et al. (2025) highlight that the trade–emissions nexus varies across income groups, underscoring the heterogeneous impact of trade depending on structural and developmental conditions. Against this background, the present study places trade openness at the core of its empirical framework, explicitly testing its role alongside other macroeconomic drivers of environmental degradation in the APEC region.

Moreover, Ozturk et al. (2024) analyze the links between ecological footprint, economic growth in South Asian countries. Using advanced panel data methods, their results support both the EKC and PHH hypotheses. While financial development promotes environmental sustainability, energy consumption worsens environmental quality. Jiang et al. (2022) examine how innovation, measured by R&D expenditure, affects carbon emissions, considering the EKC and Pollution Haven Hypotheses. Their findings present that innovation reduces emissions in high-income countries but not in others.

On the other hand, the technique effect argues that trade promotes the spread of cleaner technologies and stricter production standards, leading to improved environmental quality. In a recent panel analysis of 24 Sub-Saharan African countries countries, Mbe-Nyire Mpuure et al. (2024) indicate that trade openness contributes to emissions reduction when combined with strong institutions and green technology. Furthermore, Sun & Qamruzzaman (2024) investigate how innovation, green energy, and trade openness influence environmental sustainability in BRICS nations. Their findings support the EKC hypothesis and trade openness has mixed effects, improving efficiency.

Yingjun et al. (2024) analyze the influences of technology and trade openness on sustainability in Turkey and Egypt from 1990 to 2022. Their findings indicate that both countries experience significant environmental degradation due to higher levels of emissions and ecological footprints. While technology and trade have mixed environmental effects and support sustainable trade practices to align with the SDGs. Similarly, numerous studies (Luo et al., 2021; Qi, 2024; Zhou et al., 2025; Zugravu-Soilita, 2018) have focused on the link between trade openness and environmental issues, highlighting the complex and often context-dependent nature of this linkage.

A growing body of research has examined environmental sustainability specifically within the APEC region, underscoring the importance of trade openness and related macroeconomic factors. Kocakaya (2024) investigates trade openness and FDI across APEC countries from 1990 to 2020 and finds that while trade openness tends to increase CO_2 emissions, FDI can play a mitigating role. Similarly, Balli (2024) incorporates financial development and energy consumption into the analysis for APEC economies, showing that these factors, alongside trade, are significant drivers of emissions. Liu (2023) highlights the role of renewable energy adoption in APEC, suggesting that while renewables are crucial for lowering CO_2 emissions, their effectiveness depends on complementary factors such as trade integration and institutional quality. Navarro-Chávez et al. (2023) further explore the nexus of tourism, economic growth, and environmental degradation in APEC countries, providing evidence of the Environmental Kuznets Curve dynamics across both developed and emerging members. Collectively, these studies emphasize the heterogeneity of APEC economies and confirm the necessity of a region-specific analysis of trade openness and environmental sustainability.

2.2 Economic Growth and Environmental Sustainability

The EKC hypothesis remains a foundational concept in the field, proposing an inverted U-shaped relationship between income levels and environmental degradation (Grossman & Krueger, 1995). Several studies provide empirical support for this relationship. For instance, Şerifoğlu & Öge Güney (2024) confirm the EKC in OECD countries using total GHG emissions and renewable energy. They also find that renewable energy reduces GHG emissions. Their results highlight the need for policies promoting clean energy to achieve environmental sustainability. Later, Muratoğlu et al. (2024) study the EKC hypothesis at the sectoral levels, agriculture, industry, manufacturing, and services, for 38 OECD countries. Their results confirm the EKC for all sectors except industry and reveal asymmetric influences of energy consumption on CO_2 emissions. Agriculture contributes most to environmental degradation. Likewise, Maneejuk & Yamaka (2022) test the EKC in OECD countries using a Panel Smooth Transition Kink Regression (PSTKR) model. The results confirm an inverted U-shaped link among economic expansion and sulfur dioxide emissions, validating the EKC.

Moreover, Audi et al. (2025) explore how economic, political, and social globalization affect environmental harm in BRICS countries. Their findings confirm EKC show an inverted U-shaped link between income and emissions. Almulhim et al. (2025) analyze the influences of green energy, institutional quality, and economic expansion on consumption-based CO_2 emissions in BRICS countries. The findings reveal that economic development increases emissions, while green energy use and stronger institutions significantly reduce them.

Similarly, Zhu et al. (2024) investigate the impacts of GDP, economic globalization, and natural resource rents on ecological footprints in N-11 countries using the CS-ARDL approach. The results show that natural resource rents harm ecological quality, while GDP and globalization contribute positively to green sustainability in the long run. The study finds no evidence of an N-shaped EKC. In contrast, Prempeh (2024) explores the impact of financial development, globalization, green energy, economic expansion, and industrialization on reducing environmental degradation, employing the N-shaped EKC hypothesis. The findings conclude that the N-shaped EKC holds for the region. This shows that financial development and green energy reduce environmental harm. There are also several studies (Jahanger et al., 2023; Rabbi & Abdullah, 2024; Schneiter & Mellon-Bedi, 2025; Wang et al., 2024) that have investigated the EKC hypothesis, which conclude the existence of support for the existence of an N-shaped EKC and a U-shaped EKC.

However, the EKC is not universally applicable. In many emerging economies, economic growth is frequently linked to increased emissions because of reliance on fossil fuels and rapid industrial development. Lacheheb et al. (2015) investigate the EKC hypothesis for Algeria using the ARDL framework. The outcomes do not support the EKC hypothesis. Recently, Almeida et al. (2024) revisit the EKC hypothesis across 158 countries and 44 regions. By examining lead-lag relationships between income and CO_2 emissions, it reveals a heterogeneous EKC pattern across different income groups.

2.3 Renewable Energy and Environmental Sustainability Nexus

Renewable energy consumption is widely recognized as a key determinant of environmental improvement. Multiple studies confirm the emissions-reducing effect of renewables. For example, Dogan & Inglesi-Lotz (2020) conclude that green patents reducing CO_2 emissions in G20 countries. Likewise, Ferhi & Helali (2024) explore how green energy affects CO_2 emissions, economic expansion, and human development across 24 OECD countries. The findings show that green energy reduces emissions.

Magazzino et al. (2022) demonstrate the link between GDP, CO2 emissions, and green energy use. Their findings suggest that green energy can effectively reduce CO2 emissions lack of negatively impacting economic expansion. Moreover, Nulambeh & Jaiyeoba (2024) examines the effect of green energy and industrialization on Africa's ecological footprint. The results show that green energy falls the footprint, while industrialization increases it, negatively affecting the environment. Later, Dam et al. (2024) demonstrate the interaction between innovation, green energy use, natural resources, and ecological footprint in E-7 countries. The findings show that both innovation and green energy decrease the ecological footprint, aligning with SDGs 7 and 13.

Furthermore, Kelly & Nembot Ndeffo (2024) investigate the impact of economic complexity on environmental issues in Sub-Saharan Africa, where economic growth is accelerating. They find that economic complexity worsens the ecological footprint intensity. Lastly, Idroes et al. (2024) study the influence of economic expansion, military expenditure, green energy, manufacturing, tourism, capital formation on environmental degradation in North African countries. Their model results show that green energy, and capital formation reduce environmental degradation.

2.4 Foreign Direct Investment, Industrialization, and Urbanization

FDI can play a dual role in environmental outcomes. While it may bring cleaner technologies and better management practices (the pollution halo hypothesis), it can also worsen environmental degradation if it targets pollution-intensive sectors (Tang & Tan, 2015). Similarly, Xiao et al. (2022) explore the impact of FDI on carbon emissions in China, focusing on how institutional quality affects this relationship. The results reveal that FDI can effectively decrease emissions. Sitthivanh & Srithilat (2022) analyze the impact of FDI on environmental quality in ASEAN countries, the findings conclude that long-term economic expansion and FDI significantly impact on ASEAN's environmental quality.

Furthermore, Renyong & Sedik (2023) explores the connectedness between FDI and environmental quality in 18 East African countries. Their results reveal that while FDI can degrade environmental quality in the short term, it improves it in the long term when supported by environmental sustainability policies and institutions. Subsequently, Furtuna & Atis (2024) analyze the relationship between FDI and environmental degradation, uncovering a U-shaped dynamic. Their study finds that while rising FDI initially contributes to a reduction in carbon emissions, surpassing a certain threshold reverses this trend, leading to an increase in emissions as FDI continues to grow.

Industrialization is strongly associated with increased emissions, primarily because it involves energy-demanding activities and production processes. Studies like Zhang & Zhou (2021) show that industrial output significantly increases CO_2 emissions in BRICS countries. Likewise, urbanization influences emissions both positively and negatively. While dense urban areas can improve energy efficiency, rapid and unplanned urbanization often results in increased emissions. Poumanyvong & Kaneko (2010) found that urbanization leads to higher emissions in low-income countries but declines in developed economies. Similarly, Mahmood et al. (2020) investigate the influence of industrialization and urbanization on emissions in Saudi Arabia. The findings show that both industrialization and urbanization harm the environment.

Furthermore, Amoah et al. (2024) study how trade openness influences the interaction between industrialization and emissions in Sub-Saharan Africa. They find that industrialization increases emissions, and trade openness strengthens this relationship. There are also many studies (Hasnisah et al., 2019; Nulambeh and Jaiyeoba, 2024; Song et al., 2023; Vo et al., 2024; Yu et al., 2024) focused on industrialization and FDI, particularly examining its effects on sustainable economic growth, environmental degradation, and social transformation.

Recent studies have extended empirical evidence on trade openness and environmental effects. For instance, Dharmapriya et al. (2025) analyze the role of trade openness, energy consumption, and GDP across different income groups and highlight how energy consumption remains a principal driver of carbon emissions even under varying economic contexts. Similarly, Bakri et al. (2025) employ a threshold regression approach for selected Asian economies, showing that the relationship between trade openness and emissions may follow an inverted U-shape depending on the level of openness. Moreover, Zhou (2025) and Xuan (2025) provide more recent panel analyses linking trade openness, renewable energy, and emissions, complementing older studies and underscoring the need for robust diagnostics and methodological rigor.

2.5 Research Gaps

Although numerous studies have examined individual drivers of environmental degradation, there is still limited exploration of how the dynamic interplay between trade openness, income level, renewable energy use, innovation efforts, and other macroeconomic variables shapes environmental outcomes, particularly within the APEC region. Much of the existing research investigates these factors in isolation, without fully accounting for their interconnected effects or the complexities of cross-country heterogeneity in economic structure, environmental policy, and technological capacity. Moreover, industrialization is often proxied only by its share in GDP, which may not adequately capture sectoral composition or energy intensity, and the role of innovation is typically underexplored or measured only indirectly.

This study addresses these gaps by analyzing the long-term relationships between greenhouse gas emissions per capita and key determinants, including trade openness, income level, renewable energy consumption, and R&D expenditure, while controlling FDI, industrialization, and urbanization. Using an unbalanced panel dataset for 16 APEC member countries (1990–2023), the paper applies a robust multi-method econometric framework designed to handle challenges such as cross-sectional dependence, heterogeneity, and potential model sensitivity. By doing so, the study provides a more comprehensive understanding of how macroeconomic and policy variables jointly affect environmental degradation, offering meaningful implications for sustainable development strategies tailored to the diverse institutional and structural contexts of the APEC region.

3. Data and Methodology

This study employs an unbalanced panel dataset covering 16 selected APEC member countries over the period 1990–2023 to investigate the dynamic effects of trade openness, income level, and renewable energy consumption on environmental degradation. In addition, FDI, industrialization, and urbanization are incorporated as control variables to capture broader macroeconomic and structural influences. To mitigate data gaps and enhance panel coverage, we consulted and merged data from multiple reputable sources. For instance, renewable energy data was supplemented using IEA datasets when missing in World Bank records. Similarly, FDI and industrialization data were cross-validated with UNCTAD and OECD archives. This multi-source approach significantly reduced the degree of missingness for key variables, especially for smaller APEC economies and earlier years. To mitigate data gaps and enhance panel coverage, we consulted and merged data from multiple reputable sources. For instance, renewable energy data was supplemented using IEA datasets when missing in World Bank records. Similarly, FDI and industrialization data were cross-validated with UNCTAD and OECD archives. This multi-source approach significantly reduced the degree of missingness for key variables, especially for smaller APEC economies and earlier years.

The list of the 16 selected APEC member countries used in this study is provided in Appendix (Table 1). The dependent variable, total greenhouse gas emissions per capita (GHG), is used as a measure of environmental degradation and is sourced from the World Development Indicators (WDI) database. The GHG measure includes emissions from carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). These emissions are aggregated from key contributing sectors, namely, energy, industry, agriculture, and waste, and are standardized based on the total population of each economy. This approach ensures comparability across countries and reflects the overall environmental pressure resulting from human and industrial activities.

The main explanatory variables include trade openness (TO), defined as the sum of exports and imports as a percentage of GDP; also, GDP per capita (GDP) represents income level; and industrialization (IND), which captures the value-added share of industry in GDP, including construction.

Table 1. Variables and descriptions

Variable	Abbreviation	Description	Source
Total greenhouse gas emissions per capita	GHGC	Total greenhouse gas emissions per capita	WDI
Trade Openness	TO	Trade (% of GDP)	WDI
Gross Domestic Product per capita	GDP	GDP per capita (constant 2015 US$)	WDI
Industrialization	IND	Industry (including construction), value added (% of GDP)	WDI
Renewable energy consumption	RENEW	% of total final energy consumption	WDI
Foreign Direct Investment	FDI	net inflows (BoP, current US$)	WDI
Urbanization	URB	Urban population growth (annual %)	WDI
Research and development expenditure	RD	R&D expenditure (% of GDP)	WDI

In line with earlier studies (Hassan et al., 2024; Ilyas et al., 2024; Shah et al., 2023), this study also incorporates renewable energy consumption (RENEW), expressed as the percentage of renewable sources in total final energy consumption, to assess the transition towards clean energy. Additionally, FDI, measured as net inflows in current US dollars, is included to capture foreign direct capital inflows to the host economy. Urbanization (URB) is measured by the annual growth rate of the urban population to control demographic pressures on the environment.

To estimate the long-run relationships between greenhouse gas emissions and their indicators while addressing the econometric challenges inherent in panel data, such as correlation, potential heteroskedasticity, and unobserved heterogeneity across countries, this study adopts a stepwise multi-method approach. Specifically, Prais–Winsten regression is employed primarily as a robustness tool to address potential autocorrelation. While Prais–Winsten is conventionally designed for time-series data, in this study it is adapted to the panel context by applying the correction within each country's time dimension. This allows us to reduce bias from serial correlation in individual country series while still preserving comparability across panel units. PCSE is adopted as the main estimator given its suitability for handling cross-sectional dependence and contemporaneous correlation. RLS is subsequently used to test the stability of results in the presence of outliers, providing an additional robustness check. Although RE-GLS does not fully correct for cross-sectional dependence, it is retained for comparative purposes to illustrate how results may vary across different estimation frameworks. By sequencing the estimators in this way and applying them only after conducting diagnostic tests (e.g., cross-sectional dependence, heteroskedasticity, and stationarity tests), the study ensures that methodological choices are both transparent and appropriate to the characteristics of the dataset. The methodological framework is specifically tailored to the APEC region, where countries exhibit significant heterogeneity in economic development, environmental policies, and exposure to global economic and environmental shocks, making it essential to account for these complexities in the analysis.

With the aim of investigating the long-run relationships, the baseline regression model is specified as follows:

$$LNGHG_t = \alpha + \beta_1 LNTO_t + \beta_2 LNGDP_t + \beta_3 LNRENEW_t + \beta_4 LNFDI_t + \beta_5 LNIND_t + \beta_6 LNURB_t + \beta_6 LNRD_t + \varepsilon_t \quad (1)$$

where LNGHG represents greenhouse gas emissions per capita, LNTO measures trade openness, LNGDP denotes income level, LNRENEW denotes renewable energy, and LNFDI represents foreign direct investment, LIND captures industrialization, and LNURB denotes urbanization, and LNRD denotes research and development expenditure (% of GDP), serving as a proxy for technological progress. Also, ε_t is the error term.

Table 2 presents the statistical summary of the variables used in the study, all of which are expressed in their natural logarithmic form. Table 2 presents the descriptive statistics of the variables, detailing the mean, standard deviation, and the minimum and maximum values observed for each variable throughout the sample period. Kline (2015) suggests that skewness values greater than ±2 and kurtosis values above ±8 signify significant departures from normality.

Table 2. Descriptive Statistics

Variable	Obs	Mean	Std. dev.	Min.	Max.	Skewness	Kurtosis
LNGHG	544	0.9257	0.3537	0.192	1.462	-0.373	2.081
LNTO	544	1.789	0.2903	1.196	2.640	0.922	3.955
LNFDI	544	10.034	0.6979	7.612	11.70	0.002	3.096
LNGDP	544	4.081	0.4882	2.956	4.832	-0.177	1.783
LNIND	544	1.449	0.2052	0.618	1.686	-2.349	8.822
LNRENEW	544	1.043	0.4591	0	1.772	-0.496	2.051
URB	544	1.829	1.207	0.003	5.321	0.857	3.266
RD	544	1.308	0.077	0	5.210	1.227	3.928

The time-series plot of average greenhouse gas emissions from 1990 to 2023 reveals a general downward trend, starting at around 1.41 and dropping to approximately 1.29 by 2023, despite some fluctuations. Emissions remained stable around 1.41 until 1995, peaked slightly at 1.42 by 1998, and then began a steady decline with notable dips around 2009 (due to the global financial crisis) and 2020 (due to the COVID-19 pandemic), before stabilizing at 1.29 in recent years. This overall reduction may reflect global efforts like increased renewable energy use, improved efficiency, and climate policies such as the Paris Agreement, though the persistence of emissions above 1.25 indicates that further action is still needed to combat climate change.

The correlation matrix, as seen in Table 3, reveals insightful relationships between the dependent variable, LNGHG and the explanatory variables. Notably, LNGHG is strongly and positively correlated with LNGDP (0.8648*) and LNFDI (0.5071*), suggesting that income level and FDI are associated with increased emissions. In contrast, LNGHG shows significant negative correlations with LNRENEW (-0.5119*) and URB (-0.6151*), implying that greater reliance on renewable energy and higher levels of urbanization may contribute to emission reductions, potentially reflecting better infrastructure, energy efficiency, or environmental awareness in urban areas.

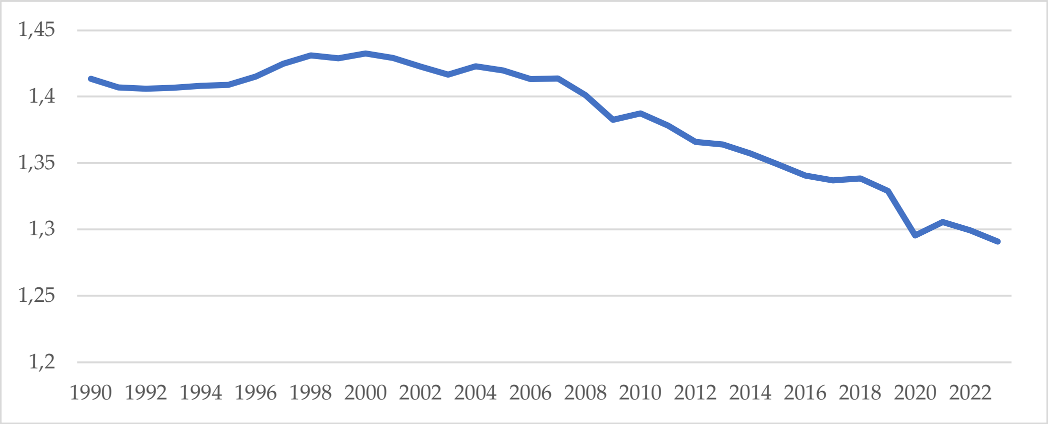

Figure 1. A time-series plot of the average greenhouse gas emissions

Moreover, trade openness (LNTO) shows a negative but statistically insignificant relationship with GHG emissions. This indicates that, at the bivariate level, trade openness does not exert a clear or robust direct effect on environmental outcomes. Also, LNGHG is negatively and significantly correlated with LNIND (-0.1587*), indicating that industrial activity may not be a major driver of emissions in this context, possibly due to cleaner technologies or structural economic shifts. Furthermore, R&D expenditure (RD) exhibits a strong and positive correlation with GHG emissions, suggesting that, at the bivariate level, higher research and development spending is associated with greater emissions. These results underscore the intricate interactions among economic, energy, and demographic variables in influencing environmental outcomes.

Table 3. Correlation matrix

	LNGHG	LNTO	LNFDI	LNGDP	LNIND	LNRENEW	URB
LNGHG	1.0000						
LNTO	-0.1597	1.0000					
LNFDI	0.5071*	-0.0644	1.0000				
LNGDP	0.8648*	-0.0155	0.4136*	1.0000			
LNIND	-0.1587*	0.1025*	-0.0554	-0.3146*	1.0000		
LNRENEW	-0.5119*	-0.2796*	-0.2232*	-0.4881*	-0.1741*	1.0000	
URB	-0.6151*	0.3078*	-0.1137*	-0.4820*	0.3267*	0.2362*	1.0000
RD	0.6708*	-0.1530*	0.3882*	0.7281*	0.0122	-0.6043*	0.3788*

Note: * denotes significance at 5% level.

Figure 2 displays the pairwise scatterplots for the variables used in the analysis. A visible positive association is observed between the GDPs per capita and greenhouse gas emissions per capita, suggesting that income level tends to increase environmental degradation. Similarly, industrialization shows a strong positive correlation with LNGHG. Conversely, there appears to be a negative link between renewable energy consumption and LNGHG.

The interaction between FDI and LNGHG is slightly positive, potentially reflecting the environmental impact of capital-intensive foreign investments. Additionally, both trade openness and urbanization show weak but slightly positive associations with LNGHG, suggesting that their influence on emissions may be more nuanced or indirect. Moreover, RD shows a clear positive association with GHG emissions, consistent with the correlation results. This suggests that, at the descriptive level, higher R&D spending in many APEC economies has coincided with higher emissions, possibly because innovation efforts are still concentrated in energy-intensive and industrial sectors. Overall, the scatterplot matrix provides preliminary visual evidence supporting the hypothesized connections between economic and environmental indicators.

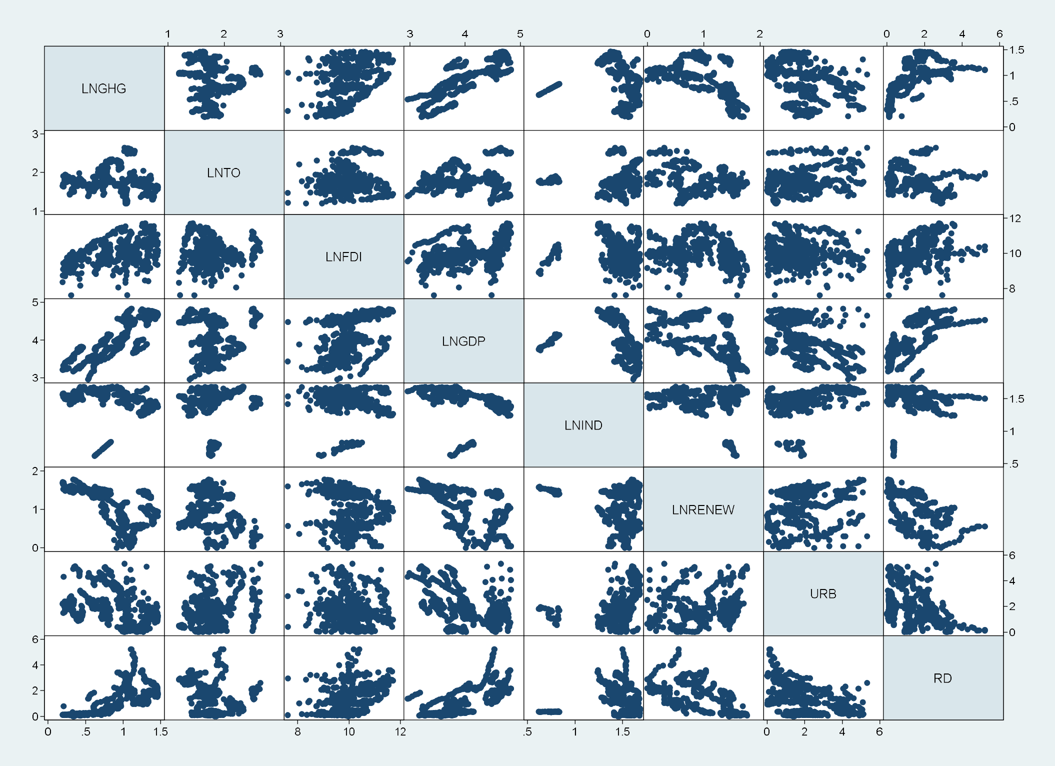

Figure 2. Scatterplot Matrix of Pairwise Variable Relationships

Table 4 presents the average values of the variables by country, highlighting substantial heterogeneity across APEC members. Developed economies such as Australia, Canada, and the United States exhibit the highest mean levels of per capita greenhouse gas emissions, whereas emerging economies such as Indonesia, Peru, and the Philippines record much lower averages but rely more heavily on renewable energy. In contrast, economies like Singapore and Malaysia show relatively low per capita emissions but very high levels of trade openness, reflecting their role as globally integrated hubs. Resource-dependent members such as Russia also differ, combining moderate emissions with relatively low trade openness.

In terms of R&D expenditure (RD), significant disparities are also evident. Advanced economies such as Japan (3.07), Korea (3.16), and the United States (2.75) allocate the highest shares of GDP to research and development, while emerging members such as Peru (0.11), the Philippines (0.14), and Indonesia (0.20) invest at much lower levels. This pattern underscores the wide technological gap within APEC, which may condition the extent to which trade openness translates into environmental improvements. Specifically, economies with higher R&D intensity may be better positioned to leverage trade for cleaner production and green technology diffusion, whereas low-R&D economies may experience limited environmental benefits. These descriptive contrasts indicate that APEC countries are far from homogeneous, which justifies the adoption of a multi-country empirical strategy.

Table 4. The means of variables by country

Country	LNGHG	LNTO	LNFDI	LNGDP	LNIND	LNRENEW	URB	RD
Australia	1.4226	1.6068	10.315	4.6923	1.4055	0.9355	1.3950	1.86
Canada	1.3323	1.8182	10.386	4.5916	1.4230	1.3418	1.3300	1.80
Chile	0.7555	1.7940	9.8279	4.0013	0.7555	1.4748	1.3355	0.36
China	0.8033	1.6086	10.912	3.5802	1.6405	1.2800	3.3917	1.62
Indonesia	0.4792	1.7103	9.7875	3.3883	1.6297	1.5625	3.3109	0.202
Japan	1.0218	1.4118	9.7656	4.5143	1.4808	0.6884	0.6452	3.07
Korea	1.0716	1.8470	9.8193	4.3158	1.5340	0.2463	0.9551	3.16
Malaysia	0.8922	2.2140	9.7219	3.8732	1.6206	0.6354	3.4739	0.84
Mexico	0.7514	1.7358	10.281	3.9703	1.5074	1.0433	1.7870	0.38
New Zealand	1.2936	1.7537	9.5126	4.5282	1.3532	1.4436	1.4362	1.22
Peru	0.3763	1.6174	9.4932	3.6371	1.4963	1.5264	1.7467	0.11
Philippines	0.2517	1.8175	9.3568	3.3551	1.5166	1.5252	1.9810	0.14
Russia	1.2001	1.7131	9.9969	3.8711	1.5141	0.5488	0.2284	1.06
Singapore	1.0850	2.5416	10.427	4.6237	1.4447	0.2623	2.4209	1.95
Thailand	0.7301	2.0480	9.7409	3.6493	1.5658	1.3543	2.6323	0.47
US	1.3443	1.3957	11.266	4.7072	1.3098	0.8214	1.2028	2.75
All countries	0.92573	1.7896	10.038	4.0812	1.4498	1.0431	1.8295	1.31

4. Empirical Results

The study spans the period from 1990 to 2023 for the selected 16 APEC countries, a timeframe chosen to capture long-run trends in greenhouse gas emissions. This section presents empirical results derived from the analysis of dynamic relationships among greenhouse gas emissions and their key determinants, including FDI, income level, trade openness, industrialization, renewable energy consumption, urbanization, RD expenditure. The findings are based on robust econometric techniques that account for cross-sectional dependence, heterogeneity, and non-stationarity within the panel data.

Given the large time dimension (T>N) of the dataset, the Breusch and Pagan (1980) Lagrange Multiplier (LM) test is deemed appropriate for detecting cross-sectional dependence. To address potential biases, the Scaled LM test developed by Pesaran (2004) and the deviation-corrected LM test by Pesaran et al. (2008) are applied. Table 5 presents the results of various cross-sectional dependence tests, including the Breusch-Pagan LM, Pesaran scaled developed by Pesaran (2004) LM, bias-corrected LM, and Pesaran CD tests, all of which indicate statistically significant dependence across all variables at the 1% level. Specifically, variables such as LNGHG, LNTO, LNFDI, LNGDP, LNIND, LNRENEW, URB, and RD exhibit significant cross-sectional dependence, suggesting the presence of interdependencies and common shocks among the panel units. This implies that environmental and economic dynamics in one country may influence or be influenced by those in others, possibly due to globalization, regional integration, or transboundary environmental effects. As a result, the existence of cross-sectional dependence highlights the necessity of employing second-generation panel data methods that can appropriately address these interlinkages, ensuring more robust and reliable empirical outcomes.

Table 5. Cross-sectional Dependence Test

Methods	LNGHG	LNTO	LNFDI	LNGDP	LNIND	LNRENEW	URB	RD
Breusch Pagan LM Test	1084.42***	844.231***	837.237***	612.42***	718.34***	839.76***	612.56***	742.23***
Pesaran scaled LM Test	54.211***	59.345***	69.567***	96.322***	75.352***	65.667***	34.562***	43.123***
Bias-corrected LM Test	62.245***	55.356***	81.467***	84.674***	32.456***	50.674***	43.235***	33.721***
Pesaran CD Test	13.567***	23.456***	24.686***	48.356***	18.345***	35.768***	19.462***	12.453***

Note: *** denotes significance at 1% level.

Table 6 reports the results of panel unit root tests using both the CIPS (Pesaran, 2007) and CADF (Hansen, 1995) methods to examine the stationarity properties of the variables. The CIPS test results indicate that most variables are non-stationary in their level form but achieve stationarity after first differencing, confirming that they are integrated of order one, I(1). Notably, LNFDI, LNGDP, URB, and RD are stationary at the 1% level in constant specifications at the level, while other variables, such as LNGHG, LNTO, and LNIND, only become stationary at first difference. The CADF test results support these findings, indicating that although a few variables like LNFDI, LNIND, and LNRENEW show stationarity at a level under trend specifications, overall, all series become stationary after taking the first difference. These consistent findings across both tests validate the appropriateness of employing econometric techniques that require variables to be I(1), such as panel cointegration for investigating the long-run relationships among the studied variables.

Table 6. Unit root test

CIPS Test (Pesaran, 2007)				
	Level		First Difference	
Variables	Constant	Constant and trend	Constant	Constant and trend
LNGHG	-1.274	-2.147	-4.817***	-5.069***
LNTO	-1.839	-2.665	-4.847***	-4.871***
LNFDI	-3.873***	-4.168***	-5.880***	-5.967***
LNGDP	-2.375**	-2.221	-3.859***	-4.116***
LNIND	-1.791	-2.661	-5.330***	-5.532***
LNRENEW	-1.670	-2.928***	-5.553***	-5.684***
URB	-2.338**	-2.433	-4.812***	-4.962***
RD	-2.674***	-2.741**	-5.015***	-5.222***
CADF Test (Hansen, 1995)				
	Level		First Difference	
Variables	Constant	Constant and trend	Constant	Constant and trend
LNGHG	-1.280	-2.251	-2.637***	-2.630***
LNTO	-1.684	-2.236	-2.808***	-2.729***
LNFDI	-2.222**	-2.558**	-4.122***	-4.199***
LNGDP	-1.984	-2.051	-2.506***	-2.809***
LNIND	-1.754	-2.604*	-3.153***	-3.172***
LNRENEW	-1.465	-2.627**	-2.626***	-3.095***
URB	-1.928*	-1.546	-2.604***	-2.713***
RD	-2.258**	-2.250	-3.221***	-3.386***

Note: Stationarity at significance level of *10%, **5%, and ***1%.

A cointegration analysis is conducted to assess the existence of a long-run relationship, and the results are presented in Table 7. Utilizing the approaches of Pedroni (2004), Westerlund & Edgerton (2007), and Kao (1999), the findings reveal a statistically significant long-term linkage between greenhouse gas emissions and all the variables considered in this study, with significance observed at the 5% and 10% levels.

Table 7. Panel Cointegration Test Results

Test	Statistic	Prob-value
Phillips–Perron t (Pedroni)	3.8315	0.0000
Dickey-Fuller t(Kao)	-1.0832	0.0011
Augmented Dickey-Fuller t (Kao)	0.4961	0.0321
Modified Dickey–Fuller t (Kao)	-1.6971	0.0448
Variance ratio (Westerlund)	17.1631	0.0000

Table 8 presents the long-run estimation results using three different econometric approaches: PCSE regression, RE-GLS regression, and Robust Least Squares. Across all models, the variable LNGDP shows a consistently significant and positive relationship with the dependent variable, indicating that income level is a key driver in the long-run dynamics. The coefficient ranges from 0.4157 in the RE-GLS regression to 0.5983 in the robust model.

Trade openness (LNTO) indicates a negative but statistically insignificant influence on the PCSE and RE-GLS regressions, whereas in the robustness model, it is negative and highly significant (-0.1075), suggesting that trade openness might decrease the dependent variable only under specific robust conditions. FDI, by contrast, exhibits highly context-dependent results. It appears statistically insignificant in the PCSE model, negative and significant in the RE-GLS estimation (-0.0216), and positive and significant in the RLS model (0.0209). These contrasting outcomes point to strong model sensitivity and reinforce the view that the environmental impact of FDI is shaped by institutional quality, sectoral allocation, and country-specific governance structures, rather than being uniform across APEC economies.

Moreover, renewable energy consumption (LNRENEW), by contrast, exerts a statistically significant negative influence in all models, indicating that increasing the share of renewable energy contributes to a reduction in the dependent variable—likely carbon emissions. This effect is strongest in the robust model (-0.0860), followed by the RE-GLS (-0.1511) and PCSE (-0.0664), all significant at the 1% level.

The industrial development variable (LNIND) is also positively and significantly associated with the dependent variable across all models, with the strongest impact observed in the RE-GLS model (0.5117), followed by the PCSE (0.1736) and the robustness model (0.1535). This confirms the important role of industrialization in shaping long-term outcomes. Lastly, the variable URB (urbanization) remains statistically insignificant across all models, suggesting that urbanization may not have a substantial direct effect on the long-run dynamics in the studied context.

The results for RD are mixed across models. In the PCSE and RE-GLS estimations, RD shows a positive and statistically significant association with GHG emissions, suggesting that higher R&D spending has, on average, coincided with greater environmental pressure in APEC economies. However, in the RLS estimation, RD turns negative and significant, implying that once outliers are accounted for, R&D may contribute to emission reductions, likely by promoting cleaner technologies in innovation-intensive economies.

Overall, the results emphasize the strong roles of income level, industrialization, and renewable energy, while also considering variables like FDI and trade openness, which show mixed findings depending on the estimation technique used.

Table 8. Long-run Estimation

Models	PCSE regression			RE-GLS regression			Robust least squares (Robustness)		
Variables	Coeffi.	Std. Err.	z-Stat.	Coeffi.	Std. Err	z-Stat.	Coeffi.	Std. Err.	z-Stat.
LNTO	-0.0111	0.015	-0.07	-0.0413	0.038	-1.05	-0.1075***	0.0290	-3.70
LNFDI	0.0021	0.001	0.74	-0.0216**	0.008	-2.57	0.0209**	0.0115	1.82
LNGDP	0.5373***	0.024	21.84	0.4157***	0.058	7.10	0.5983***	0.0256	23.34
LNIND	0.1736***	0.034	5.00	0.5117***	0.160	3.19	0.1535***	0.0251	6.11
LNRENEW	-0.0664***	0.016	-3.98	-0.1511**	0.063	-2.41	-0.0860***	0.0227	-3.78
URB	-0.0115	0.001	-0.35	-0.0181**	0.004	-1.84	-0.0135***	0.0093	-0.38
RD	0.0221***	0.005	0.39	0.026***	0.007	3.69	-0.026**	0.011	2.31
C	-1.4613***	0.119	-12.21	-1.0515***	0.398	-2.63	-1.6734***	0.1740	-9.61

Note: ***, **, and * denote statistical significance at the 1%, 5% and 10% levels.

Subsequently, we utilize the Dumitrescu & Hurlin (2012) Granger non-causality test as seen in Table 8. The results of the Dumitrescu-Hurlin test provide significant insights into the dynamic relationships among key economic variables. The findings reveal that all variables significantly granger-cause GHG. Conversely, GHG also significantly grangercauses all variables, indicating a bidirectional causality between all variables, except for urbanization.

Table 9. Panel Causality Test Results

Null Hypothesis	W-Stat	Zbar-Stat	Probability
LNGHG → LNTO	3.5575	3.1151	0.0018
LNTO → LNGHG	5.0180	6.0361	0.0005
LNGHG → LNFDI	3.9231	3.8462	0.0001
LNFDI → LNGHG	3.9050	3.8101	0.0001
LNGHG → LNGDP	3.8048	3.6095	0.0003
LNGDP → LNGHG	6.8670	9.7341	0.0000
LNGHG → LNIND	4.149	4.058	0.0000
LNIND → LNGHG	5.011	5.226	0.0000
LNGHG → LNRENEW	3.0346	2.0693	0.0385
LNRENEW → LNGHG	3.2902	2.5805	0.0099
LNGHG → URB	6.3489	8.6978	0.0000
URB → LNGHG	2.7052	1.4104	0.1584
LNGHG → RD	7.837	6.055	0.0022
RD → LNGHG	5.821	4.823	0.0001

5. Discussion

Our findings offer both confirmation and nuance relative to existing literature. For instance, consistent with Dogan & Inglesi-Lotz (2020) and Ferhi & Helali (2024), we observe a robust negative effect of renewable energy consumption on GHG emissions, underscoring the global mitigation potential of clean energy strategies. Similarly, the positive correlation between economic growth and emissions supports early-stage EKC dynamics, echoing results from middle-income contexts (e.g., Ilyas et al., 2024; Shahbaz et al., 2022), though we do not find the inverted-U form reported in some OECD contexts (e.g., Muratoğlu et al., 2024). Our findings offer both confirmation and nuance relative to existing literature. For instance, consistent with Dogan & Inglesi-Lotz (2020) and Ferhi & Helali (2024), we observe a robust negative effect of renewable energy consumption on GHG emissions, underscoring the global mitigation potential of clean energy strategies. Similarly, the positive correlation between economic growth and emissions supports early-stage EKC dynamics, echoing results from middle-income contexts (e.g., Ilyas et al., 2024; Shahbaz et al., 2022), though we do not find the inverted-U form reported in some OECD contexts (e.g., Muratoğlu et al., 2024).

Regarding trade openness, our results are mixed—significant negative under RLS but insignificant in other specifications. This aligns with Managi et al. (2009) and Mbe-Nyire Mpuure et al. (2024) who report context-sensitive effects, unlike Zhou (2025) or Bakri et al. (2025) that report stronger mitigating effects. Notably, a recent study by Shabir et al. (2023), using AMG and CCEMG estimators for APEC, found that environmental-related innovation and institutional quality reduce emissions, while trade openness and economic growth increase them. This suggests that the environmental potential of trade may only emerge in conjunction with innovation and governance.

Our FDI findings also reflect heterogeneity observed in the literature: the mixed sign across models aligns with the contrasting pollution-haven and pollution-halo perspectives (e.g., Tang & Tan, 2015; Xiao et al., 2022). For industrialization, our positive regression effects but negative bivariate correlation mirror concerns raised by Mahmood et al. (2020) about the limitations of using industry's share in GDP as a proxy.

Finally, the mixed and model-dependent effect of R&D expenditure parallels findings from innovation-focused studies that emphasize the conditional role of technological progress in engendering greener outcomes (e.g., Jiang et al., 2022; Dogan & Inglesi-Lotz, 2020).

In summary, these comparisons reinforce that the drivers of GHG emissions in APEC economies are multidimensional and structurally varied. They affirm the necessity of tailored, multifaceted policy strategies that integrate trade, innovation, energy, and governance.

Overall, our findings highlight both consistent patterns, such as the strong role of economic expansion and the mitigating effect of renewable energy, and model-sensitive results, including those for trade openness, FDI, and R&D. By clarifying these nuances and situating them within broader theoretical debates (e.g., pollution haven vs. halo, EKC dynamics), this study provides a more balanced and critical interpretation of the trade–environment nexus in APEC economies. This discussion also addresses methodological sensitivities across estimators, ensuring that the conclusions drawn are both transparent and robust.

6. Conclusion and Policy Suggestions

This study provides empirical insights into the dynamic relationships between trade openness, income level, renewable energy consumption, and environmental degradation, measured by per capita GHG emissions, across 16 selected APEC member economies over the period 1990–2023. By employing a robust econometric framework that accounts for cross-sectional dependence, heteroskedasticity, and unobserved heterogeneity, the analysis captures the complex interactions among macroeconomic variables, structural transformations, and environmental outcomes within the diverse APEC countries.

The empirical results highlight three key findings. First, economic expansion emerges as a significant long-term drive of environmental degradation across all models, supporting the initial phase of the EKC hypothesis. Although the EKC hypothesis is not formally tested through an inverted-U shaped specification, the results are suggestive of its early-stage dynamics, wherein rising income levels correlate with increased environmental degradation. This interpretation is consistent with prior findings in middle-income economies (e.g., Ilyas et al., 2024; Shahbaz et al., 2022) but should be treated as indicative rather than conclusive.

Second, renewable energy consumption consistently exhibits a negative relationship with GHG emissions across all estimation techniques, underlining the effectiveness of clean energy strategies in curbing environmental degradation. Third, industrialization shows a strong and positive correlation with emissions, confirming that industrial expansion, especially in energy-intensive and manufacturing sectors, remains a major contributor to environmental harm.

Fourth, the results for R&D expenditure (RD) are mixed and model-sensitive. While PCSE and RE-GLS estimations indicate a positive and significant relationship between RD and emissions, suggesting that innovation spending in many APEC countries is still directed toward conventional and energy-intensive sectors, the robust least squares (RLS) estimator reveals a negative and significant coefficient, implying that once outliers are addressed, R&D foster cleaner technologies and contribute to emission reductions in innovation-intensive economies. These findings highlight the importance of distinguishing between general innovation and targeted green innovation when evaluating the environmental role of R&D.

The results for FDI also reveal considerable heterogeneity across models—negative in some estimations, positive in others, and insignificant in certain cases. This variability underscores the contested role of FDI in the environmental economics literature. On the one hand, FDI can stimulate industrial growth and increase emissions when directed toward pollution-intensive sectors, consistent with the pollution-haven hypothesis. On the other hand, it can also serve as a channel for cleaner technology transfer and improved management practices under stronger regulatory environments, reflecting the pollution-halo hypothesis. The mixed outcomes in our analysis therefore highlight that the environmental impact of FDI in APEC economies is highly context-dependent, shaped by institutional quality, sectoral composition, and the degree of environmental governance in the host country.

While trade openness appears with a negative coefficient in most specifications, its effect is statistically insignificant in PCSE and RE-GLS and becomes significant only under the RLS estimator, which is particularly sensitive to outliers. This pattern suggests that the environmental effect of trade openness is not robust across models and should be interpreted with caution. The results imply that trade can contribute to emission reduction under certain conditions, such as the presence of strong environmental regulations, clean technology diffusion, and supportive institutional frameworks.

Urbanization, in contrast, does not show a significant long-run effect on emissions, possibly due to offsetting dynamics between increased consumption and urban efficiencies. The statistical insignificance of urbanization in the long-run estimations may be attributed to offsetting effects within the APEC region. Likewise, increasing urban populations can lead to greater energy demand and infrastructure expansion, which are typically associated with higher emissions. On the other hand, urban areas often achieve efficiency gains through improved public transportation, compact settlement patterns, and better access to clean technologies. Furthermore, the urbanization indicator used, urban population growth, may not fully capture qualitative differences in urban planning, energy efficiency, or infrastructure sustainability, which are critical to understanding its environmental impact.

The Dumitrescu-Hurlin panel Granger causality tests reveal widespread bidirectional relationships between emissions and nearly all explanatory variables. While such results may initially appear overly extensive, they likely reflect the high degree of economic and environmental interdependence among APEC economies, where growth, trade, and energy transitions are mutually reinforcing. At the same time, the sensitivity of the Dumitrescu-Hurlin test to large panels can also contribute to this outcome. Therefore, these findings should be interpreted as indicative of complex feedback mechanisms, such as emissions driving policy adjustments, while economic activities simultaneously fuel emissions, rather than as universal causal linkages.

The empirical findings of this study highlight the need for a multidimensional and integrated policy approach to achieve environmental sustainability within the APEC region. The dynamic interplay among economic expansion, industrialization, green energy use, trade openness, and FDI requires nuanced strategies that account for both macroeconomic development and ecological balance. These findings are also directly aligned with the United Nations Sustainable Development Goals (SDGs), providing region-specific insights into their implementation.

First, promoting sustainable economic growth is essential. The results consistently indicate that economic expansion is a significant long-run driver of GHG emissions. This suggests that while growth remains a key policy objective, it must be pursued in a manner that internalizes environmental externalities. APEC member economies should adopt green growth frameworks that integrate environmental considerations into their development plans. This recommendation is consistent with SDG 8 (Decent Work and Economic Growth) and SDG 13 (Climate Action).

Second, accelerating the transition to green energy emerges as a critical priority. Policymakers should therefore prioritize investments in green energy sources, such as solar, wind, and hydro power. Financial incentives such as tax breaks, subsidies, and green bonds can stimulate private sector involvement, while public-private partnerships can enhance the pace of deployment. Modernizing energy grids and removing structural barriers to renewable adoption will further strengthen the decarbonization trajectory. These measures directly advance SDG 7 (Affordable and Clean Energy) and SDG 13.

Third, greening the industrial sector is indispensable for achieving long-term sustainability. The positive and significant association between industrialization and emissions suggests that industrial activities continue to be a major source of environmental pressure in APEC countries. Governments must facilitate the transition toward cleaner production methods through energy efficiency, circular economy principles, and green technologies. Given these results, policies aimed at greening industry should not only focus on reducing the overall share of industry in GDP but also target improvements in energy efficiency and cleaner production processes, since aggregate indicators may conceal persistent emission-intensive activities. This aligns with SDG 9 (Industry, Innovation, and Infrastructure) while reducing conflicts with SDG 13.

Fourth, reforming trade and investment governance is crucial to align openness with environmental responsibility. These findings imply that trade openness can support environmental sustainability only when combined with stringent environmental standards, green technology transfer, and effective governance. Without such conditions, the relationship remains ambiguous. Environmental clauses in trade and investment agreements, technology transfer, and stricter controls on pollution-intensive capital inflows can ensure that globalization supports sustainability. This recommendation contributes to SDG 17 (Partnerships for the Goals) and strengthens linkages between SDG 13 and global economic integration. Fifth, urban planning and sustainable urbanization policies must be prioritized, even though urbanization did not show a significant long-run effect in this study. Integrated strategies for compact, energy-efficient, and low-carbon cities—such as investments in public transport, green buildings, and smart infrastructure—remain vital. This is closely linked to SDG 11 (Sustainable Cities and Communities).

Sixth, strengthening innovation systems with a clear green orientation is critical. The results show that R&D expenditure exerts mixed effects on emissions—positive in conventional models but negative when outliers are controlled for—implying that the environmental benefits of R&D are not automatic. General innovation spending may still be directed toward traditional, energy-intensive sectors in many APEC economies. Therefore, policies must ensure that R&D investment is explicitly targeted toward green technologies, renewable energy innovations, and resource-efficient production. This aligns closely with SDG 9 (Industry, Innovation, and Infrastructure) and reinforces synergies with SDG 13 (Climate Action). Green-oriented innovation incentives, such as dedicated funds for environmental R&D, intellectual property protection for green technologies, and cross-border cooperation in innovation, can transform R&D into a more consistent driver of decarbonization.

Finally, strengthening regional cooperation and policy coordination is essential given the institutional and developmental heterogeneity within the APEC region. Regional collaboration can facilitate the sharing of best practices, harmonization of environmental standards, and joint initiatives on clean technology transfer. Such cooperation reinforces commitments under the Paris Agreement and supports collective progress toward SDG 13 and SDG 17.

Overall, this study contributes to the environmental economics literature by explicitly acknowledging the complexity of macroeconomic–environment interactions. The analysis strengthens the justification of results by clarifying where findings are consistent, where they diverge, and why these divergences may occur. By doing so, it offers not only empirical evidence but also a robust and transparent interpretation that aligns with ongoing academic debates and policy needs.

Future studies could extend this analysis by explicitly examining the post-pandemic era and the impact of recently adopted environmental policies. While this study treats 1990–2023 as a continuous period to ensure consistency across the estimations, a separate assessment of the post-2020 period could yield valuable insights into how COVID-19 disruptions and new climate commitments reshape the trade–emissions nexus in APEC economies.

A key limitation of this study is that, although cross-sectional dependence has been confirmed, certain estimators applied (e.g., RE-GLS) are not fully equipped to account for this issue. While the use of PCSE and RLS helps to mitigate some of these challenges, future research could further enhance robustness by incorporating second-generation estimators such as the Common Correlated Effects Mean Group (CCEMG) or the Augmented Mean Group (AMG), which are specifically designed to address cross-sectional dependence in heterogeneous panels. A further limitation of the present study is that the estimators employed do not fully address potential endogeneity. Although Granger causality tests were applied to assess directional linkages, future research could enhance robustness by employing second-generation panel methods such as System-GMM or CCEMG, which explicitly account for endogeneity and cross-sectional dependence. Another limitation concerns the measurement of industrialization, which in this study is proxied solely by the share of industry in GDP. While this indicator allows cross-country comparability, it does not capture structural aspects such as energy intensity or sectoral composition, which may explain the inconsistency observed between correlation and regression results. Future studies should therefore consider more refined indicators of industrial activity to provide a more accurate assessment of its environmental impact.

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Appendix. List of APEC Countries

Table 1. List of APEC Countries

Australia	Canada	Chile	China
Indonesia	Japan	Korea	Malaysia
Mexico	New Zealand	Peru	Philippines
Russia	Singapore	Thailand	US