



*Research article*

## **Analyzing the nexus between green finance, green production practices, and environmental quality in an Era of geopolitical uncertainty**

**Ahsan Anwar<sup>1,2,3,\*</sup> and Ali Abbas<sup>4</sup>**

<sup>1</sup> UCSI Graduate Business School, UCSI University, Kuala Lumpur, Malaysia

<sup>2</sup> Faculty of Economics and Business, Universitas Airlangga, Surabaya, Indonesia

<sup>3</sup> College of International Studies, Korea University, Seoul, South Korea

<sup>4</sup> National Institute of Public Policy, National School of Public Policy, Lahore, Pakistan

\* **Correspondence:** Email: [ahsananwar@ucsiuniversity.edu.my](mailto:ahsananwar@ucsiuniversity.edu.my).

**Abstract:** Achieving carbon neutrality targets through environmentally friendly initiatives and green financing has become a global focus. This study examined the impact of economic growth, green finance, geopolitical risk, green production practices, and urbanization on carbon emissions in the context of G7 economies for the time period of 1994–2020. Using a panel quantile regression method, the study captured heterogeneous environmental impacts of explanatory factors. Findings reveal that economic growth has a positive impact on carbon emissions. However, this impact is low in upper quantiles. Green finance has a negative relationship with carbon emissions, depicting the supportive role of green financing to achieve environmental sustainability. Geopolitical risk shows adverse environmental outcomes, which calls for geopolitical stability to avoid disruptions in implementing green initiatives. Results show a negative link between green production practices and carbon emissions, validating the pivotal contribution of ecologically sustainable manufacturing activities to enhance environmental quality in G7 nations. Conversely, urbanization has a positive impact on carbon emissions, emphasizing the need for greener urban planning strategies. In light of these empirical outcomes, we recommend fostering green finance (SDG-12), implementing green production practices (SDG-9), curbing geopolitical risks (SDG-16), enhancing environmentally sustainable economic growth (SDG-8), and improving green urban planning strategies (SDG-11) for advancing carbon neutrality (SDG-13) in G7 economies.

**Keywords:** green finance; geopolitical risk; green production practices; environmental quality; sustainable development goals

**JEL Codes:** G28, F51, Q55, Q50, Q01

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## 1. Introduction

Achieving environmental sustainability through reduced carbon emissions has become a global priority for preserving long-term prosperity and mitigating climatic challenges (Chen et al., 2022; Zheng et al., 2024). According to the 13<sup>th</sup> Sustainable Development Goal (SDG) established by the United Nations, global net carbon emissions must be reduced by 45% between 2010 and 2030 to effectively curb global warming and sustain a temperature rise within 1.5 °C (Thapa et al., 2023). The COP28 (United Nations Climate Change Conference) reaffirmed the urgency for sustainable development and climate action (Lu et al., 2024). Fossil fuels, including natural gas, coal, and oil, are the main contributors of carbon emissions, while enhanced manufacturing, transportation networks, and energy production support economic development (Wang et al., 2023). Increased carbon emissions deteriorate ecosystems, cause extreme weather conditions, and escalate climate change. These ecological issues pose severe risks for food insecurity, economic instability, and health vulnerabilities, making sustainability a crucial component of contemporary policy.

In recent literature, green finance has evolved as a central determinant for environmental sustainability through diverting capital toward environmentally friendly technologies and sustainable renewable energy usage (e.g., Meo and Abd Karim, 2022; Chen and Chen, 2021; Zhang et al., 2025). Empirically, green finance has gained the global attention of policymakers due to factors including climate change, rising carbon emissions, and inefficient conventional financing (Amighini et al., 2022; Akomea-Frimpong et al., 2022). Additionally, rising public ecological awareness, worldwide net-zero transition initiatives, and corporate obligations for sustainable development have promoted the significance of green finance as a fundamental mechanism for channelizing public and private investment toward renewable energy utilization and cleaner production methods, which ensure sustainable development (Qi et al., 2023; Simeon et al., 2024). Green finance supports reduced carbon emissions, enhanced air quality, and growing cleaner manufacturing structures. In the presence of green finance, strengthened environmental governance encourages the objective of sustainable economic transition among governments, financial institutions, and private investors (Sun, 2022; Wang et al., 2023). Hence, green finance is highly emphasized globally, not only as a complementary measure but as a significant supportive factor of economic development and environmental sustainability.

Increasing geopolitical risks (GPR) reduce the effectiveness of green finance by diverting financial resources toward risk management and geopolitical stability, which delays financial support for climate action and sustainable investment (Dong et al., 2023; Lorente et al., 2023). Militarization itself is highly resource- and carbon-concentrated, causing land deterioration, deforestation, and loss of biodiversity due to resource extraction, infrastructure devastation, and weapon testing (Ahmed, 2024; Sovacool et al., 2023). Additionally, GPR leads to a decline in long-term green financing by uplifting financial and political risks, while weakening renewable energy adoption and green finance growth in vulnerable regions (Mertzanis and Tebourbi, 2025; Wang et al., 2024). Geopolitical tensions

not only cause environmental damage but also delay worldwide sustainability and climate initiatives (Khan et al., 2024). Thus, curbing GPR is also crucial to develop environmental sustainability.

Most existing studies emphasize traditional, fossil fuel-based production methods, whereas the contribution of green production practices (GPP) to environmental sustainability remains relatively underexplored. GPP contributes to enhancing sustainable development through transitioning from traditional production processes to energy-efficient and circular manufacturing practices (Baah et al., 2021). Such practices focus on renewable energy usage, environmentally friendly raw materials, waste management, greener technologies, life cycle valuation, and recycling, while restricting CO<sub>2</sub> emissions and natural resource depletion (Xiao et al., 2025). By integrating low-carbon technologies and encouraging energy efficiency, GPP supports climate mitigation and enable environmental sustainability. Additionally, GPP is an effective measure for aligning industrial structure processes with worldwide sustainability initiatives, particularly SDGs related to environmental protection and climate action (Centobelli et al., 2020). Consequently, GPP has become a significant contributor to environmental quality in the developing and developed world.

Economic growth, while important for improving per capita income, developing human welfare, and achieving overall socioeconomic objectives, yields severe environmental implications through heavy natural resource stress and carbon emissions. The environmental Kuznets curve (EKC) hypothesis (Grossman and Krueger, 1995) states that when economies focus on increasing economic output without considering strict environmental regulations, this leads to environmental degradation, deforestation, biodiversity loss, and air and water pollution, due to a reliance on conventional energy sources, widening industrial structure, and urbanization. In the absence of green production methods, technological innovations, and environmentally friendly industrial expansion, mainly developing nations face an adverse linkage between growth and environment (Hashmi et al., 2025; He et al., 2021). However, with technological advancements and a transition to a knowledge-based economy, economic growth can be accompanied by energy-efficient output processes, whereas financial growth enables ecologically supportive clean energy infrastructure and environmental protection (Ganda and Panicker, 2025). Therefore, evaluating economic growth through an environmental perspective is critical to explore whether development processes are environmentally supportive or harming ecological sustainability. Among key environmental factors, the literature highlights the implications of urbanization. Rapidly growing urban centers enhance transportation, industrial activities, construction, and energy usage, which results in carbon emissions, waste generation, and environmental pollution (Sun et al., 2019; Hilali and Neffati, 2025). Thus, urbanization becomes a fundamental factor in examining environmental sustainability due to its potential to reshape the natural environment.

G7 economies, comprising advanced industrial countries (Canada, France, Italy, Japan, the United Kingdom, the United States, and Germany), cover a substantial share of the world's GDP, energy consumption, and greenhouse gases. Furthermore, G7 countries have relatively similar environmental strategies, institutions, and financial markets, making these advanced economies a suitable group for empirical estimations to provide theoretical evidence-based policy suggestions for improving environmental quality. Therefore, the present study conducts an empirical analysis to investigate the impact of green finance, green production practices, geopolitical risks, economic growth, and urbanization on carbon emissions in G7 nations.

This study contributes both theoretically and practically to the existing literature on environmental economics by providing distribution-sensitive estimations of the responsible factors of carbon emissions in G7 nations. Regarding the theoretical perspective, the study expands the traditional

growth–environment nexus by incorporating largely unexplored factors, including green finance, geopolitical risks, green production practices, economic growth, and urbanization, as explanatory factors of environmental quality. The study explains how cleaner production frameworks and green financing mechanisms interrelate with urban settings and macroeconomic expansion, with existing worldwide geopolitical instability. By taking GPR as a structural factor of environmental degradation, this study explores an innovative dimension that highlights the implications of external political shocks in lowering ecological gains even in developed countries. From a methodological perspective, this study applies a panel quantile regression (PQR) approach, instead of conventional mean-based regression techniques. The PQR method helps in capturing the heterogeneous linkage between explanatory variables with different quantiles of carbon emissions. To assess the robustness of these findings, the regression model is revised by replacing green production practices with technological innovations. The study makes a practical contribution by giving actionable policy measures to attain environmental sustainability through reducing carbon emissions in advanced and high-carbon-emitting nations. The empirical outcomes of the study provide data-driven guidance for developing targeted green financing (SDG-12), improving cleaner production methods (SDG-9), handling urban ecological pressures (SDG-11), and safeguarding sustainable development from geopolitical risks (SDG-16). As a whole, this research enhances the debate on sustainable finance and green growth in G7 economies, while supporting the worldwide transition toward the net-zero target (SDG-13) by providing policy-relevant insights from the most influential economic region.

### *1.1. Research questions:*

RQ1: How does economic growth affect CO<sub>2</sub> emissions in G7 economies?

RQ2: What is the impact of green finance on CO<sub>2</sub> emissions in developed countries?

RQ3: Does geopolitical risk contribute to CO<sub>2</sub> emissions in G7 countries?

RQ3: What role do green production practices play in improving environmental quality?

RQ5: How does urbanization affect the environmental quality in developed countries?

This study is organized into four sections. Section 2 reviews empirical and theoretical literature, explaining key concerns of the existing literature and theoretical channels of each explanatory variable of the study. Section 3 covers methods, model of the study, and econometric techniques, which are applied to capture heterogeneous links of green finance, GPR, GPP, economic growth, and urbanization on different levels of carbon emissions in G7 economies. Section 4 contains results and discussions, stating interpretations and valuable insights for the G7 region. Section 5 concludes the study and presents policy implications to enhance environmental quality in G7 economies.

## **2. Literature review**

This section provides a comprehensive empirical and theoretical review of the literature to explore key factors of environmental quality, including green finance, geopolitical risk, green production practices, economic growth, and urbanization. It incorporates theories and frameworks of connectivity between socioeconomic factors and environmental quality. This section is subdivided into empirical and theoretical literature.

## 2.1. Empirical literature

### 2.1.1. Green finance and environmental quality

Zhou et al. (2020) conducted panel estimations for 30 provinces in China to evaluate environmental and economic outcomes of green finance. Using the generalized least squares (GLS) regression method, the study found a positive link between green finance and environmental sustainability and economic prosperity. However, the effect of green finance in improving environmental quality was not the same for different levels of economic development. Zhou et al. (2023) reported a supportive link between green finance and financial innovations with environmental quality through declining greenhouse gases in China. This linkage was found using the ARDL method, and remained significant in both the short-run and long-run. Other works also highlighted the favorable role of green finance in environmental quality in BRICS nations (Sahoo et al., 2024; Tang et al., 2025) and OECD economies (Umar and Safi, 2023; Wang et al., 2023; Alvi et al., 2025). Conversely, Sethi et al. (2024) revealed that green finance, institutional quality, and green technology utilization were positively linked with emissions in developing nations. Moreover, renewable energy was found to have a negative coefficient value for carbon emissions. In selected Asian economies, Saleem et al. (2022) evaluated the nexus between green finance and environmental deterioration by applying CS-ARDL and AMG regression techniques. The study used environmental tax as a measure of green financing and found a significant negative linkage between green financing and environmental degradation. Shen et al. (2024) suggested that green finance is helpful for achieving sustainable development. Hanafy et al. (2025) also reported a significant favorable contribution of green finance in improving environmental quality among the top 25 green-finance-practicing global economies. The study emphasized the need to develop green infrastructure through green financial initiatives to achieve sustainable development.

### 2.1.2. Geopolitical risk and environmental quality

Pata et al. (2024) evaluated the influence of GPR and energy security risk on environmental quality in four fragile economies: India, Brazil, Turkey, and South Africa. Using quantile regression methods, the study revealed an adverse linkage of geopolitical risk and energy security risk with load capacity factors (proxy for environmental quality). Similarly, in G20 nations, Wang et al. (2024) examined the association between GPR and ecological footprint for 2000–2021. Using a method of moment quantile regression, FMOLS, and DOLS, the study found a positive, significant link between geopolitical risk and ecological footprint, suggesting measures for improving geopolitical stability to attain environmental quality. Khan et al. (2023) analyzed the empirical link between GPR, militarization, and economic policy uncertainty with environmental degradation in BRICS nations. Findings showed a positive influence of GPR and militarization on greenhouse gases and a negative link with economic uncertainty, emphasizing measures to overcome geopolitical tensions for achieving sustainable development in BRICS economies. Applying panel quantile regression, Khan et al. (2024) explained the association between GPR and economic policy uncertainty with environmental sustainability in BRICST nations for 1990–2020. Results showed a negative linkage of GPR and economic policy uncertainty with load capacity factor, recommending enhancing economic and geopolitical stability for environmental sustainability. Likewise, geopolitical risks declined

environmental quality in various regions, including G8 nations (Foglia et al., 2025), E7 economies (Chu et al., 2023), OECD countries (Liu, 2025), the Middle East and Africa (Abouelenein et al., 2026), and Asian countries (Khan et al., 2025).

### 2.1.3. Green production practices and environmental quality

He et al. (2021) found a varying role of agricultural green production innovations on low-carbon efficiency. The study concluded that technological suitability and local conditions matter when adopting agricultural green production innovations to improve sustainable outcomes in the case of mainland China. Baah et al. (2021) investigated the linkages between GPP, environmental performance, and progress of SMEs in developing nations. By applying a partial least squares structural equation modeling method, significant supportive implications of GPP were found in improving environmental quality and reputation of firms. Likewise, Xiao et al. (2025) examined the empirical relationship between green production practices and environmental quality among Asian economies for 1990–2020. A panel quantile regression revealed a positive impact of green production practices on environmental quality through a significant reduction in carbon emissions. Taking the load capacity factor as a proxy for environmental sustainability, Hashmi et al. (2025) analyzed environmental outcomes of green production practices, renewable energy use, FDI, and geopolitical risk among G7 nations. Findings showed an adverse link of GPP and a supportive role of GPR, FDI, and renewable energy use for environmental sustainability.

### 2.1.4. Economic growth, urbanization, and environmental quality

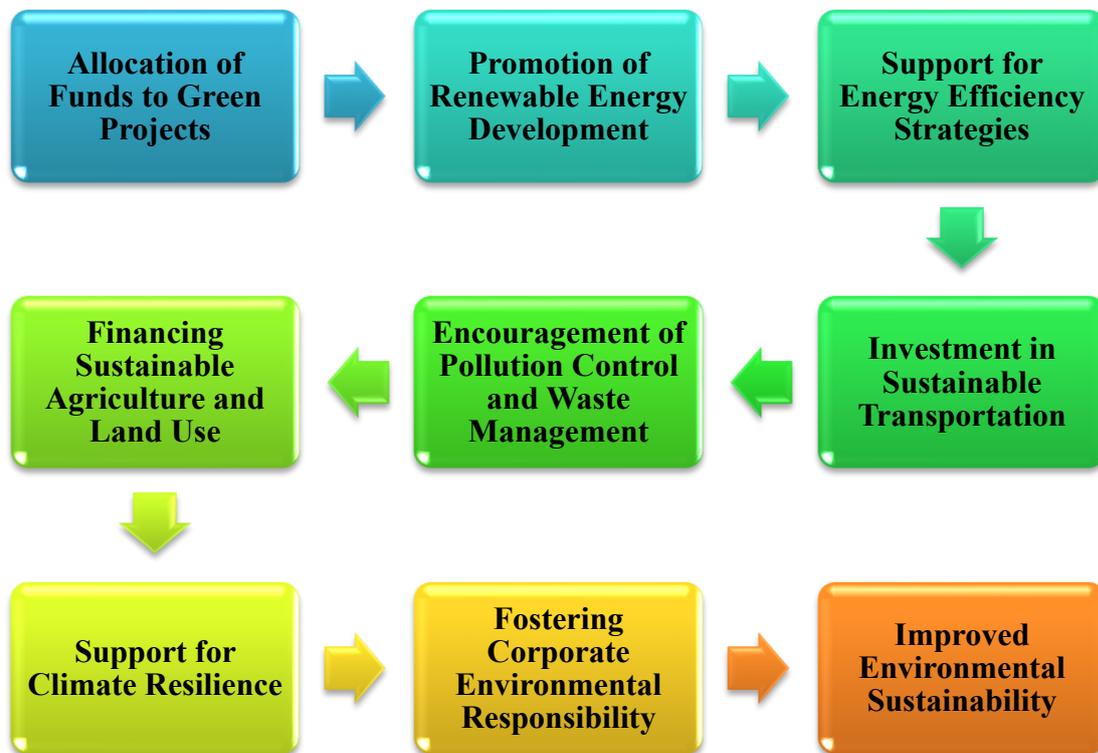
Sun et al. (2019) conducted a panel study among 31 provinces of China to evaluate the influence of economic growth and urbanization on environmental pollution. Using spatial econometric estimations, results showed a positive impact of urbanization on environmental pollution, while economic growth had mixed outcomes (environmentally supportive for nearby provinces and adverse roles for local provinces). Nurjanana et al. (2025) analyzed the nexus between EG and environmental quality for a panel of Indonesian regions. Findings showed a positive and significant contribution to enhanced environmental quality. Another study revealed a bidirectional causality between economic growth and environmental quality and suggested sustainable growth measures. Among BRICS+ nations, Hilali and Neffati (2025) examined links between urbanization, economic growth, and globalization and the environmental performance index (EPI). Outcomes revealed unfavorable environmental links of EG and globalization. Urbanization had mixed linkages: environmentally supportive through infrastructure development and efficient policies, and adverse through resource stress. Using data for 1990–2001 for Malaysia, Begum et al. (2025) investigated the impact of EG, urbanization, energy use, and population size on carbon emissions. Findings of ARDL, FMOLS, and DOLS revealed positive coefficients of all explanatory variables, showing adverse implications for environmental quality. The study also advocated for sustainable and inclusive measures of urbanization along with green growth initiatives.

### 2.1.5. Research gaps

The existing literature on environmental sustainability covered numerous socioeconomic determinants; however, some gaps remain. Previous studies analyzed the role of economic growth, urbanization, and green finance on environmental quality while excluding green production practices in such a framework. Despite the existing literature, which has examined geopolitical risks as significant determinants of environmental quality, gaps remain for the inclusion of GPRs in the methodological framework of green finance and green production practices. To fill these gaps, this study conducted an inclusive analysis covering the joint implications of green finance, geopolitical risks, green production practices, economic growth, and urbanization in G7 nations.

## 2.2. Theoretical literature

### 2.2.1. Theoretical linkage: Green finance and environmental quality



**Figure 1.** Theoretical linkage between green finance and environmental quality.

The theoretical channel of green finance in improving environmental quality is based on sustainable development theory (Brundtland, 1987; Holden et al., 2014; Shi et al., 2019). This theory emphasizes enhanced economic output without compromising the environmental needs of present and future generations. Through green finance, financial resources are allocated to environmentally friendly projects, including sustainable agriculture, renewable energy, and eco-friendly production mechanisms. This way, green finance helps in decreasing carbon emissions and preserving natural resources, which ultimately ensures environmental sustainability. Likewise, the environmental

Kuznets curve (EKC) hypothesis, proposed by Grossman and Krueger (1995), also explains that when economies have sufficient finance to promote green initiatives in the production process, further economic growth leads to a reduction in carbon emissions, instead of elevating pollution. Figure 1 shows the theoretical association between green finance and environmental quality.

### 2.2.2. Theoretical linkage: Geopolitical risk and environmental quality

According to conflict theory, large and powerful entities, including political elites and industries, exploit small groups and environmental resources. These geopolitical tensions and conflicts lead to unsustainable extraction, rent-seeking, and environmental deterioration (Song et al., 2024; Cao et al., 2024). According to the resource curse hypothesis, in the presence of geopolitical instability, resource-rich economies face resource exploitation, which aggravates environmental pollution (Murshed and Rahman, 2025). When significant resources, including gas, oil, or minerals, become strategically imperative, local elites, military groups, and external actors compete to earn resource rents, leading to poor governance, corruption, and undermined ecological regulations. Consequently, economies face deforestation, biodiversity loss, and land degradation (Wang et al., 2023). Figure 2 represents the theoretical linkage between geopolitical risks and environmental quality.



**Figure 2.** Theoretical linkage between geopolitical risks and environmental quality.

### 2.3.3. Theoretical linkage: Green production practices and environmental quality

In the context of ecological modernization theory, innovative policy systems and technologically based industries support in sustaining growth and preserving environmental resources (Spaargaren and Mol, 1992; York and Rosa, 2003). This theory explains that technological innovations promote renewable energy use, environmentally friendly production processes, and energy-efficient machinery, which alleviates ecological pollution (Bugden, 2022). The innovation diffusion theory describes how

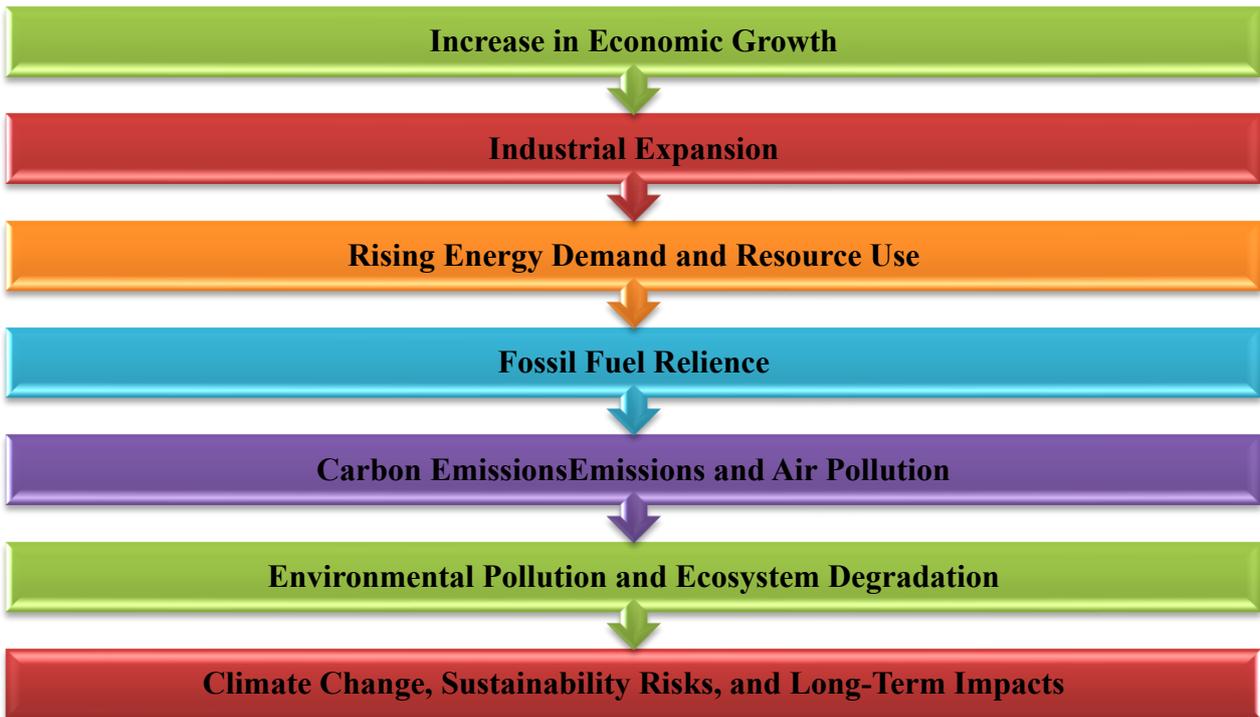
innovative practices and technologies penetrate among industries, societies, and organizations (Rogers et al., 2014). This theory also emphasizes the significance of knowledge sharing, communication networks, and institutional strengths in stimulating green technology adoption. Figure 3 shows the theoretical link between green production practices and environmental quality. Through the adoption of green production practices, the reliance on non-renewable energy usage and resource stress decreases, which eventually lowers waste and carbon emissions, while improving environmental quality.



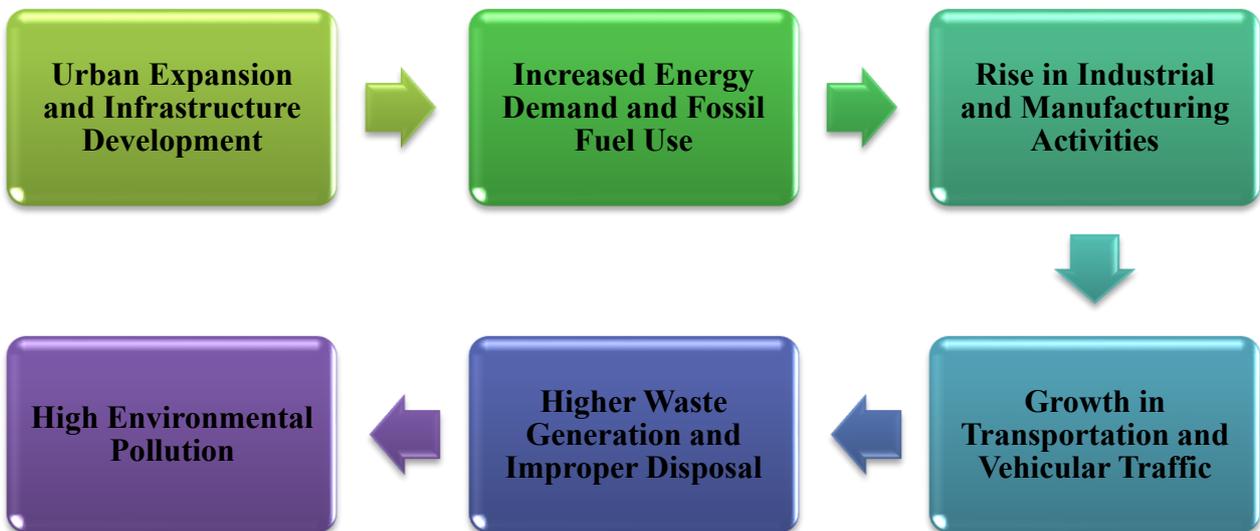
**Figure 3.** Theoretical linkage between green production practices and environmental quality.

#### 2.3.4. Theoretical linkage: Economic growth, urbanization, and environmental quality

The EKC hypothesis (Grossman and Krueger, 1995) explains the nexus between EG and environmental quality, which consists of two phases and is presented as an inverted U-shaped curve. At an initial stage, economic growth leads to high carbon emissions due to traditional production methods, urbanization, and heavy reliance on fossil fuels. After achieving a certain level of economic growth, economies adopt greener technologies, efficient production processes, and effective ecological regulations, which help to reach a later phase, where environmental quality improves, coupled with economic prosperity. Figure 4 represents how an increase in economic growth weakens environmental sustainability due to energy demand, industrialization, and dependence on fossil fuels.



**Figure 4.** Theoretical linkage between economic growth and environmental quality.



**Figure 5.** Theoretical linkage between urbanization and environmental quality.

Urban expansion deteriorates the environment by enhancing vehicle emissions, unregulated and environment-harming industrialization, and extensive energy utilization (Khan et al., 2025; Yusuf, 2023). According to urban ecology theory, growing urbanization increases the demand for ecological resources, including energy, water, and materials; in turn, it produces heat, heavy waste, and carbon emissions

(Niemela, 1999; Parris, 2018). Figure 5 shows the urbanization–environment linkage: urbanization increases carbon emissions by intensive fossil fuel usage, manufacturing activities, and high vehicular traffic.

### 3. Methods

This section explains the study model and specifies the variables and econometric methods to estimate the effects of explanatory factors on carbon emissions in G7 nations.

#### 3.1. Model

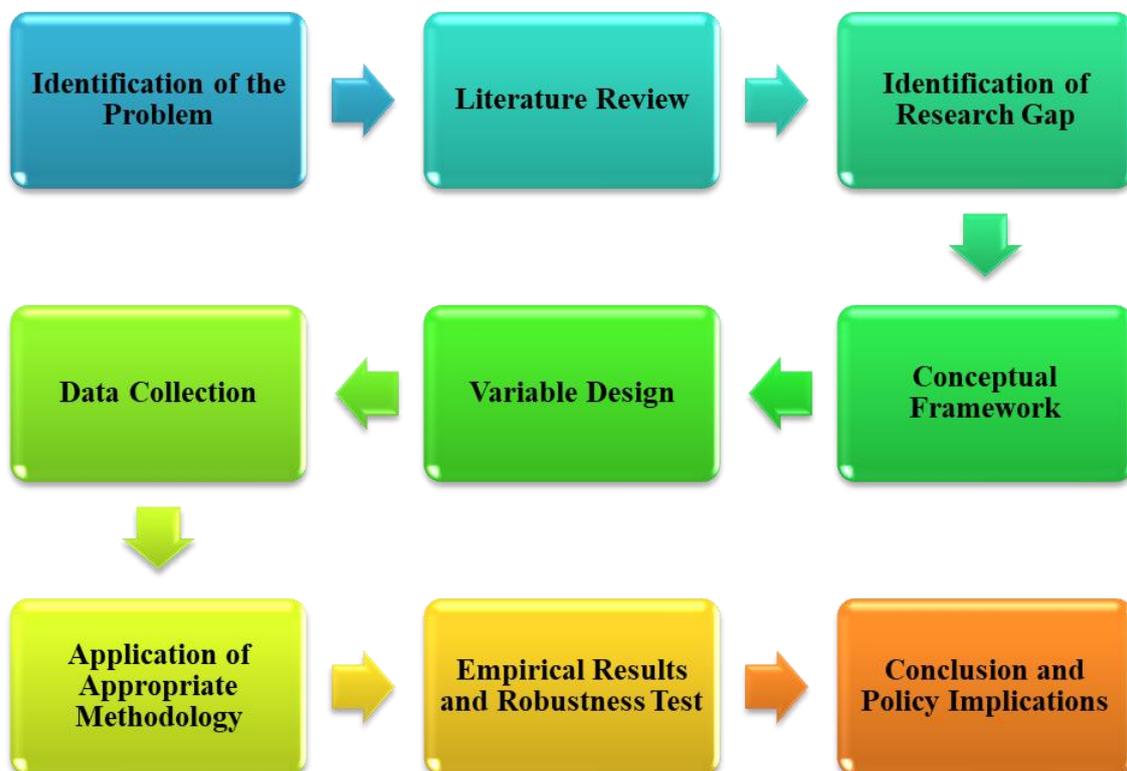
This study examines the empirical heterogeneous impact of economic growth (EG), green finance (GF), geopolitical risk (GPR), green production practices (GPP), and urbanization (URB) on carbon emissions (CO<sub>2</sub>) in G7 nations (Canada, France, Italy, Japan, the United Kingdom, the United States, and Germany). Equation 1 represents the functional form of the model.

$$CO_2 = f(EG, GF, GPR, GPP, URB) \quad (1)$$

This model hypothesizes a positive effect of GPR and URB on carbon emissions, whereas EG, GF, and GPP present a negative link with environmental degradation. Equation 2 shows the econometric form of the model.

$$CO_{2it} = \alpha_i + \beta_1 EG_{it} + \beta_2 GF_{it} + \beta_3 GPR_{it} + \beta_4 GPP_{it} + \beta_5 URB_{it} + \varepsilon_{it} \quad (2)$$

Where  $\alpha$ ,  $\beta$ , and  $\varepsilon$  represent the constant term, coefficients, and error term, respectively. In addition,  $i$  and  $t$  symbolize the country and time. Figure 6 presents the study road map of the present study in detail.



**Figure 6.** Study's road map.

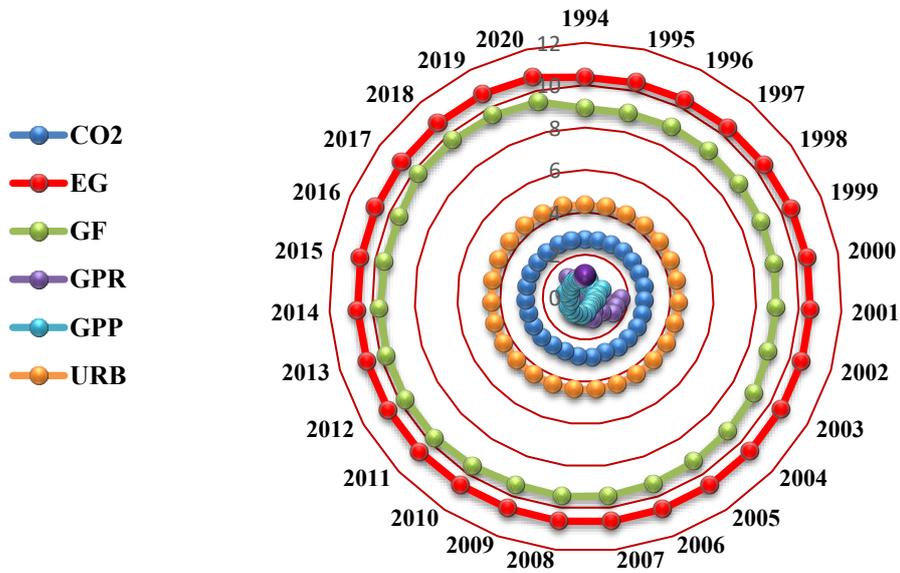
### 3.2. Data

This study investigates the varying relationship of EG, GF, GPR, GPP, and URB with CO<sub>2</sub> in G7 economies, using an empirical dataset for 1994–2020. Data for CO<sub>2</sub>, EG, and URB was obtained from World Development Indicators (WDI), published by the World Bank (2024). Data for green finance and green production practices were obtained from OECD (2024). This study measures green finance by an environmental tax, following the study of Sinha et al. (2023), who suggested that by adopting the Pigouvian mechanism, the tax revenue might be directed to finance green-energy-related projects. Similarly, Sachs et al. (2019) stated that the government should gradually increase the carbon tax and use this revenue for funding green energy projects. The GPR Index, as calculated by Caldara and Iacoviello (2022), is used to represent geopolitical instability. Variable specifications are given in Table 1. Figure 7 shows the data trends of all variables for each country.

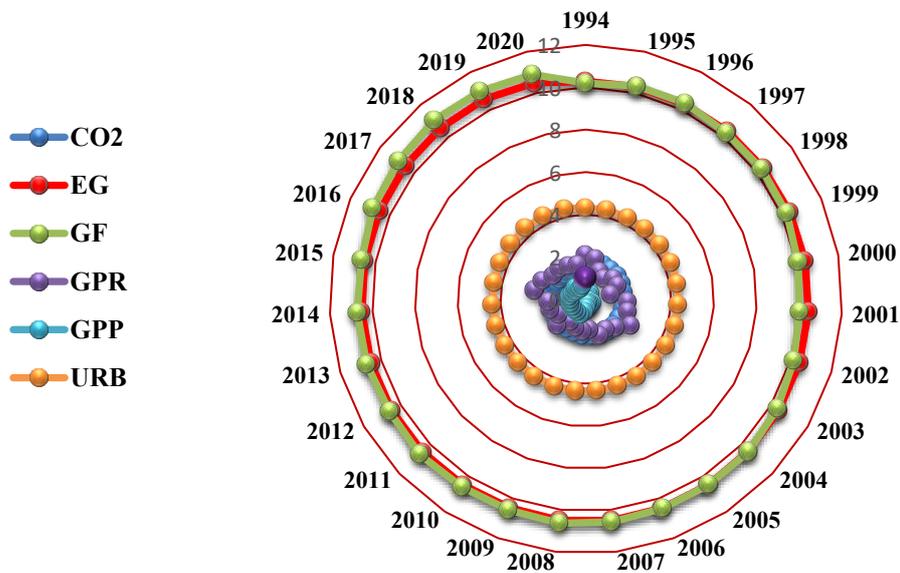
**Table 1.** Description of the variables

Variables	Abbreviations	Measurement scale/proxy	Position in study	Data source
CO <sub>2</sub> emissions	CO2	CO <sub>2</sub> emissions (metric tons per capita)	Dependent variable	World Bank (2024)
Economic growth	EG	GDP per capita (constant US dollar, 2015)	Independent variable	World Bank (2024)
Green finance	GF	Environmentally related tax revenue (million US dollars)	Independent variable	OECD (2024)
Geopolitical risk	GPR	GPR Index of Caldara and Iacoviello (2022), based on the frequency of newspaper articles containing the words “geopolitical tensions” and “geopolitics”, among others	Independent variable	Policyuncertainty.com
Green production practices	GPP	Climate change mitigation technologies in the production or processing of goods (% of all technologies)	Independent variable	OECD (2024)
Technological innovation	TIN	Patent applications, residents plus non-residents	Independent variable	World Bank (2024)
Urbanization	URB	Urban population (% of total population)	Independent variable	World Bank (2024)

### Canada

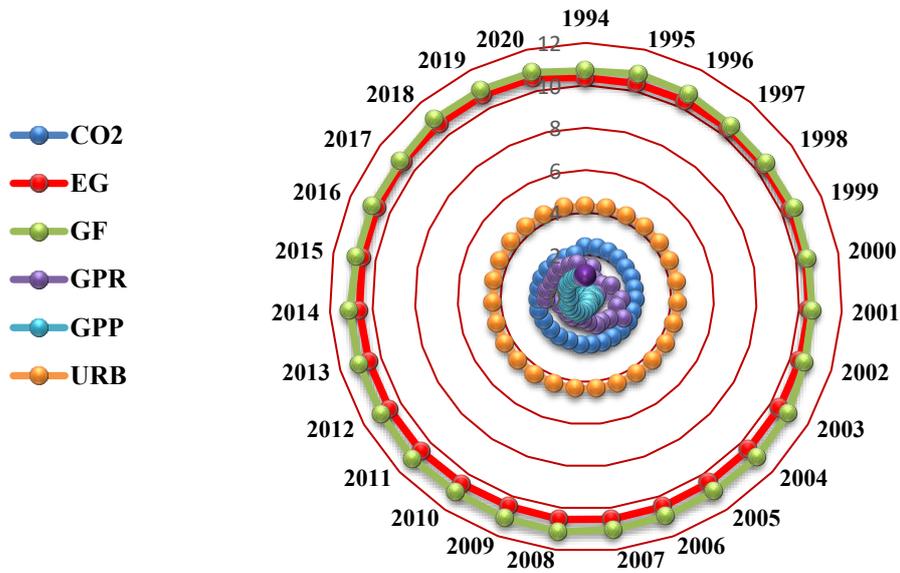


### France

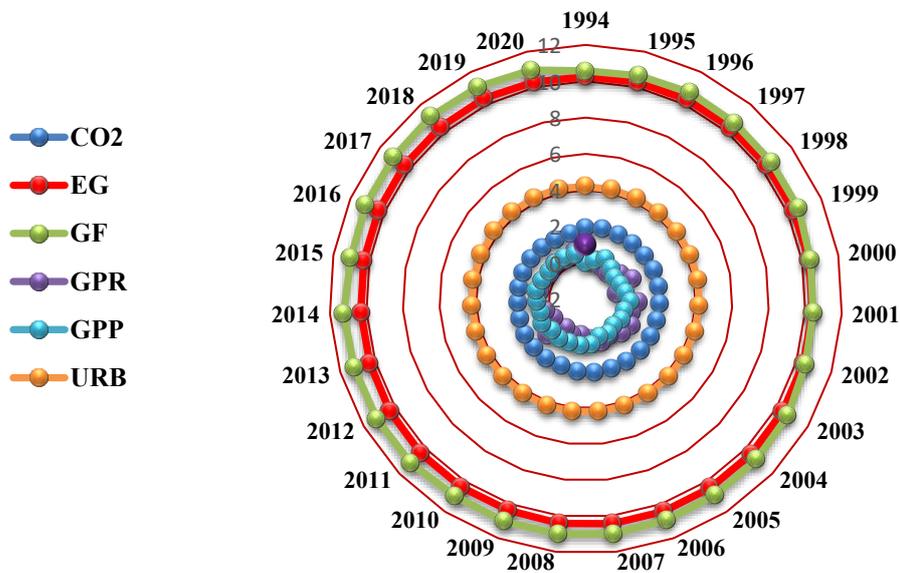


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### Germany

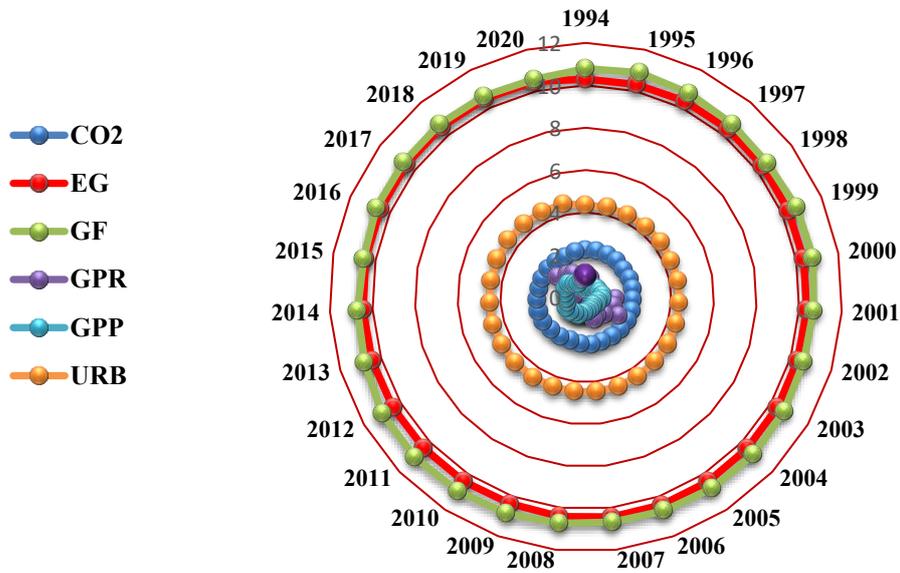


### Italy

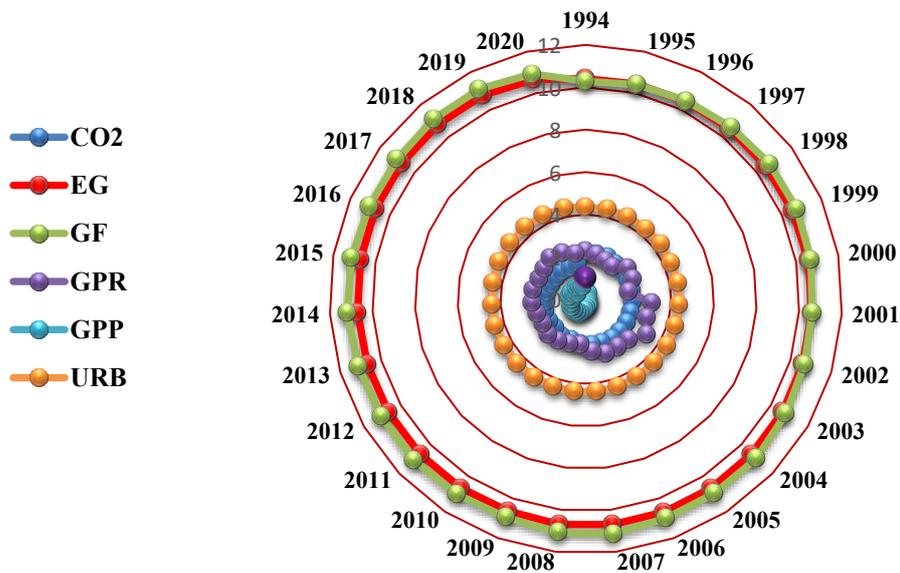


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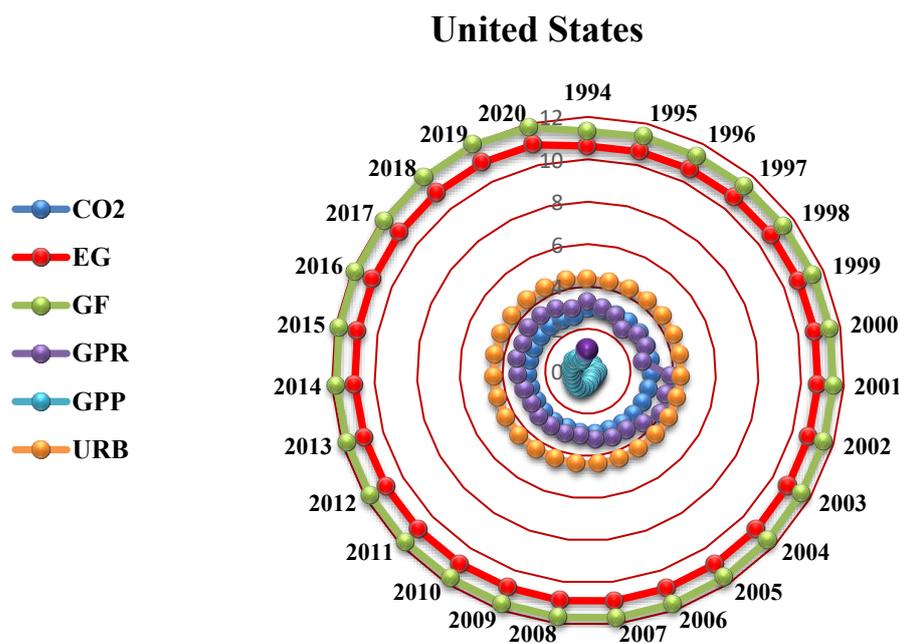
### Japan



### United Kingdom



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**Figure 7.** Country-wise trends of the dataset.

### 3.3. Econometric methods

The study uses the panel unit root test to assess the stationarity of the variables, panel cointegration techniques to confirm the existence of cointegration among the variables, and the panel quantile regression approach to capture long-run linkages.

#### 3.3.1. Panel unit root

To assess the stationarity of variables, panel unit root tests are employed, which capture time series and cross-sectional variations. By evaluating heterogeneity among entire cross-sections, these tests resolve the limiting issue of low power in traditional unit root methods. In the current study, Im, Pesaran, and Shin (IPS) and ADF-Fisher tests are employed to assess the presence of unit roots. As an extension of the test in Levin et al. (2002), the IPS method allows for heterogeneity in each unit root process across-sectional units. In the presence of heterogeneous stochastic properties in cross-sections, the IPS test becomes a more reliable and flexible method to check stationarity. Equation 3 shows the IPS test, based on cross-sectional average of individual ADF statistics.

$$\Delta y_{it} = \sigma_i + \varphi_i y_{it-1} + \sum_{j=1}^k \alpha_j \Delta y_{it-j} + \theta_i t + \vartheta_t + \epsilon_{it} \quad (3)$$

The ADF Fisher unit root test, proposed by Maddala and Wu (1999), is also used to check stationarity, as given In equation 4.

$$\tau = -2 \sum_{i=0}^n \ln \rho_i \quad (4)$$

In the above equation,  $\rho_i$  symbolizes the probability values for each ADF unit root test for each  $i$  cross-section.

### 3.3.2. Panel cointegration techniques

To estimate the presence of long-run linkages among the variables of the study, Johansen–Fisher and Kao Cointegration techniques are used. The panel Johansen–Fisher test, developed by Maddala and Wu (1999), provides two statistics, trace and eigenvalue, for individual cross-sections through probability values. By using Equation 5, the Johansen–Fisher test combines the p-values of each cross-section.

$$\chi^2 = -2 \sum_{i=1}^N \ln (\rho_i) \quad (5)$$

Where the null hypothesis represents an absence of cointegration based on a chi-square distribution. There is cointegration among variables when the Fisher statistics become significant. This test is also more useful than single equation tests as it handles multiple cointegration vectors and employs the maximum likelihood method, allowing for cross-sectional heterogeneity in dynamics and long-term linkages. Additionally, the Kao cointegration test, proposed by Kao (1999), estimates cross-sectional dependence and assumes a cointegration vector.

### 3.3.3. Panel quantile regression method

The panel quantile regression (PQR) technique is applied to estimate the long-term association of explanatory variables with carbon emissions. The econometric form of the PQR approach is presented in Equation 6.

$$CO2_{it} = \beta_{\vartheta} X_{it}^{\circ} + \varepsilon_{it}; \text{Quant}_{\vartheta}(CO2_{it}|X_{it}) = \beta_{\vartheta} X_{it}^{\circ} \quad (6)$$

In equation 6, the vector of independent variables (EG, GF, GPR, GPP, and URB) is denoted as  $X^{\circ}$ , the residual vector is symbolized as  $\varepsilon$ , and the conditional quantile of the dependent variable carbon emissions is shown as  $\text{Quant}_{\vartheta}(GGDP_{it}|X_{it})$ . The PQR method was proposed by Koenker and Bassett Jr (1978) and helps to estimate the influence of a covariate on the overall conditional distribution of the dependent variable. The simple OLS approach evaluates this impact only on the conditional average of the dependent variable. The PQR also becomes appropriate when data are skewed and present outliers. Usually, economic variables have the issue of non-normality due to economic shocks such as banking crises, financial crises, or pandemics; in such conditions, the mean-based method is unable to provide true outcomes. Therefore, this study uses the panel quantile regression, which provides coefficients at lower, middle, and higher quantiles, according to the nature of dataset.

## 4. Results and discussion

Descriptive statistics show significant distributional properties and variability of the variables for G7 nations (Table 2). The dependent variable “carbon emissions” has a mean value of 2.255 and a standard deviation of 0.419, depicting limited cross-nation dispersion in carbon emissions. Economic growth progress is stable and less volatile, with a standard deviation of 0.177. However, high variability in the scale and depth of green finance is shown by the high standard deviation (0.635) and a mean value of 10.881. Similarly, the GPR index among G7 nations shows heavy fluctuations, with

a standard deviation of 0.989. In contrast, green production practices show a low mean value (0.561) with limited fluctuations (standard deviation of 0.268), highlighting uneven adoption. Technological innovations show a mean value of 10.884 and a standard deviation of 1.372. Urbanization, with a mean value of 4.359, highlights the high urbanization level among G7 nations. Percentile distributions (25<sup>th</sup>, 50<sup>th</sup>, and 75<sup>th</sup>) illustrate a consistent rise in carbon emissions, followed by an increase in green finance, GPP, GPR, economic growth, and urbanization. This mechanism highlights that high levels of emissions are linked with higher economic activity, technological adoption, financial expansion, and growing GPR and urban population among G7 countries. Carbon emissions and GPR are positively skewed, showing occasionally high emissions and geopolitical risks, while GPP, GF, and URB are negatively skewed. Jarque–Bera values represent nonnormality for all variables except urbanization at the 5% significance level, showing the existence of outliers; therefore, a robust analysis method like quantile approaches is suitable for regression analysis.

**Table 2.** Descriptive statistics

	CO <sub>2</sub>	EG	GF	GPR	GPP	TIN	URB
Mean	2.255	10.542	10.881	1.560	0.561	10.884	4.359
Percentile 25	1.947	10.404	10.652	0.7132	0.351	9.735	4.333
Percentile 50	2.218	10.498	11.059	1.448	0.587	10.495	4.365
Percentile 75	2.729	10.658	11.244	2.315	0.766	12.578	4.395
Maximum	3.018	11.013	11.951	3.955	1.029	13.339	4.519
Minimum	1.495	10.255	9.106	-0.298	-0.010	8.916	4.202
Std. Dev.	0.419	0.177	0.635	0.989	0.268	1.372	0.072
Skewness	0.199	0.675	-1.140	0.437	-0.296	0.487	-0.249
Kurtosis	2.000	2.707	3.961	2.268	2.087	1.848	3.463
Jarque–Bera	9.108	15.041	48.261	10.248	9.329	17.928	3.658
P-value	0.010	0.000	0.000	0.005	0.009	0.000	0.160
Observations	189	189	189	189	189	189	189

**Source:** Author's calculations

**Table 3.** Correlation matrix

Variables	CO <sub>2</sub>	EG	GF	GPR	GPP	URB
CO <sub>2</sub>	1	0.541	-0.173	0.256	0.143	0.262
EG	0.541	1	0.271	0.726	0.306	0.403
GF	-0.173	0.271	1	0.448	0.098	0.114
GPR	0.256	0.726	0.448	1	-0.096	0.312
GPP	0.143	0.306	0.098	-0.096	1	0.527
URB	0.262	0.403	0.114	0.312	0.527	1

Table 3 presents the correlation matrix, showing a positive correlation of carbon emissions with all explanatory variables, excluding green finance, with values of 0.54 (economic growth), -0.17 (green finance), 0.14 (green production practices), 0.25 (geopolitical risk), and 0.26 (urbanization). These values highlight that higher economic growth and urbanization have a high, increasing link with emissions; such a link with green production practices is weak. However, higher green finance leads to lower carbon emissions. As a whole, the correlation matrix indicates moderate correlations and not high multicollinearity, which allows the inclusion of these variables in conducting empirical estimations.

**Table 4.** Unit root tests

Indicator	Results of IPS test		Results of ADF test	
	At level	At 1 <sup>st</sup> difference	At level	At 1 <sup>st</sup> difference
	t-statistics	t-statistics	t-statistics	t-statistics
CO <sub>2</sub>	3.314	-6.085***	3.195	-5.851***
EG	0.921	-3.668***	1.034	-3.481***
GF	-0.192	-5.901***	-0.142	-5.796***
GPR	-0.150	-6.360***	-0.861	-9.743***
GPP	-0.121	-9.238***	-0.100	-7.928***
TIN	-0.232	-3.661***	-0.145	-3.751***
URB	3.379	-6.953***	2.880	-12.082***

Source: Author's calculations. \*\*\* significance at 1%.

The outcomes of unit root tests are given in Table 4. Both IPS and ADF tests provide similar results, showing all variables (dependent and independent) stationary at the first difference with a 1% level of significance. Stationarity of data implies that estimated linkages are not spurious.

**Table 5.** Johansen–Fisher and Kao tests

a) Johansen–Fisher and Kao cointegration tests				
Hypothesized	Fisher stat.*			
No. of CE(s)	From trace test	p-value	From max-eigen test	p-value
None	26.74	0.020	26.74	0.020
At most 1	283.6	0.000	203.4	0.000
At most 2	244.8	0.000	162.9	0.000
At most 3	126.5	0.000	85.03	0.000
At most 4	61.91	0.000	47.43	0.000
At most 5	43.40	0.000	43.40	0.000
b) Kao cointegration test				
ADF			t-statistics	p-value
			-1.796	0.036

Source: Author's calculations.

Table 5 presents the cointegration estimates of Johansen–Fisher and Kao cointegration methods. In the Johansen–Fisher test, the null hypothesis is rejected based on the significant statistics of the trace test (26.74, 283.6, 244.8, 126.5, 61.91, and 43.4) and maximum eigenvalues (26.74, 203.4, 162.9, 85.03, 47.43, and 43.4) with a 1% significance level. This implies the presence of long-term cointegration among the variables. The Kao test also confirms cointegration through significant ADF statistics (-1.796) with a 5% significance level. Overall, both tests validate the stable equilibrium relationship among G7 nations and allow for further regression estimations.

**Table 6.** Findings of panel quantile regression

Panel quantile regression results										
Variables	Values	Grid of quantiles								
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
EG	Coeff.	1.760***	2.523***	2.000	1.963***	1.956***	1.709***	1.320***	1.108***	0.964***
	St. Er.	0.088	0.059	1.413	0.043	0.050	0.299	0.029	0.014	0.011
GF	Coeff.	-0.479***	-0.236***	-0.206	-0.161***	-0.174***	-0.200***	-0.235***	-0.245***	-0.253***
	St. Er.	0.006	0.026	0.282	0.003	0.009	0.029	0.007	0.0021	0.002
GPR	Coeff.	-0.181***	-0.287***	-0.241	-0.187***	-0.145***	-0.062	0.044***	0.109***	0.129***
	St. Er.	0.011	0.015	0.211	0.011	0.013	0.063	0.007	0.002	0.003
GPP	Coeff.	0.047	-0.418***	-0.332	-0.288***	-0.331***	-0.251**	-0.207***	-0.136***	-0.266***
	St. Er.	0.063	0.051	0.294	0.021	0.005	0.109	0.015	0.005	0.008
URB	Coeff.	-0.779***	0.629**	1.298***	1.265***	1.377***	1.367***	1.191***	1.168***	1.493***
	St. Er.	0.117	0.255	0.248	0.029	0.011	0.139	0.107	0.019	0.028

Source: Author's estimation. \*\*\*, \*\*, and \* represent significance at the 1%, 5%, and 10%, respectively.

The PQR method results are given in Table 6, containing regression coefficients, standard error, t-statistic, and probability values of each variable for all quantiles (Q0.10–Q0.90). First, results show a positive and significant impact of EG on carbon emissions across all quantiles, except Q0.30, highlighting adverse EG implications for environmental quality in G7 nations. This linkage is high (1.760 to 2.523) in the lower quantile, mainly due to an initial stage industrial scale effect and heavy energy dependence. However, in the middle and upper quantiles, this adverse effect becomes weaker, with a consistent decline in positive coefficients (1.963–0.964). This partially supports the EKC hypothesis, where positive coefficients decline but do not become negative. Literature also provides evidence for a similar nexus, depicting the unfavorable role of economic growth on environmental quality (Hilali and Neffati, 2025). Second, green finance has a supportive role in decreasing carbon emissions. The coefficient values are negative and significant (–0.200 to –0.479). Green finance improves sustainable development through reducing carbon emissions by directing financial capital toward cleaner production mechanisms and sustainable lending (Holden et al., 2014; Shi et al., 2019). Third, GPR has a negative impact on carbon emissions in the lower and middle quantiles, and a positive linkage in the upper quantile. This implies that, initially and due to the high GPR, economic activities slowdown, which reduces emissions. However, at upper quantiles, G7 economies utilize energy-intensive production methods, which leads to high carbon emissions. A wide range of literature reveals adverse environmental outcomes of GPR (Murshed and Rahman, 2025; Song et al., 2024). Fourth, results show a negative linkage of green production practices with carbon emissions, which indicates a significant contribution of GPP to environmental degradation in G7 economies. This implies that growing GPP leads to renewable energy use, ecological manufacturing processes, and energy-efficient machinery, which ultimately improve environmental quality in G7 countries (Bugden, 2022; Rogers et al., 2014). Lastly, urbanization has a positive and significant link to carbon emissions, depicting the adverse environmental outcomes of rapidly expanding cities. Without environmental regulation, an increase in urbanization enhances resource stress, transportation pressure, and inappropriate land use, ultimately causing environmental degradation (Parris, 2018; Khan et al., 2025).

**Table 7.** Panel quantile regression (robustness test)

Panel quantile regression results with technological innovations as the independent variable (robustness test)										
Variables	Values	Grid of quantiles								
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
EG	Coeff.	1.231***	1.250***	1.334**	1.321***	1.341***	1.399***	1.316***	1.345***	1.369***
	St. Er.	0.007	0.013	0.559	0.018	0.011	0.009	0.011	0.005	0.004
GF	Coeff.	-0.501***	-0.465***	-0.478***	-0.480***	-0.475***	-0.461***	-0.471***	-0.445***	-0.446***
	St. Er.	0.001	0.001	0.137	0.003	0.001	0.001	0.002	0.001	0.001
GPR	Coeff.	-0.024***	-0.063***	-0.078	-0.074***	-0.040***	-0.028***	-0.005*	-0.013***	-0.025***
	St. Er.	0.002	0.004	0.103	0.002	0.002	0.002	0.003	0.001	0.001
TIN	Coeff.	0.287***	0.293***	0.302***	0.312***	0.317***	0.311***	0.338***	0.350***	0.399***
	St. Er.	0.0001	0.001	0.059	0.002	0.004	0.001	0.001	0.002	0.001
URB	Coeff.	-2.685***	-2.481***	-2.677***	-2.910***	-3.044***	-3.040***	-3.307***	-3.227***	-3.400***
	St. Er.	0.033	0.020	0.500	0.027	0.047	0.008	0.014	0.023	0.012

Source: Author's estimation. \*\*\*, \*\*, and \* represent significance at 1%, 5% and 10%, respectively.

For robustness, the model was re-estimated by replacing GPP with technological innovations. The findings, given in Table 7, show similar linkages of all variables with baseline estimations, including economic growth, urbanization, green finance, and geopolitical risks. Technological innovations have a positive, significant impact on carbon emissions. This contrasts with the environmentally supportive role of green production practices, indicating that technologies without green preferences do not

potentially enhance environmental quality but lead to more emissions. These results ensure robustness by emphasizing that innovations are central to environmental quality while adopting greener and energy-efficient technologies.

**Table 8.** Quantile slope equality test

Quantile slope equality test results				
Evaluation		Chi-Sq. statistic	Chi-Sq. d.f.	Prob.
Wald test		183.5386	40	0.0000
Quantiles	Variable	Restr. value	Std. error	Prob.
0.1, 0.2	EG	-0.763103	0.623998	0.2214
	GF	-0.242826	0.140997	0.0850
	GPR	0.106537	0.127660	0.4040
	GPP	0.465840	0.187210	0.0128
	URB	-1.409473	2.025393	0.4865
0.2, 0.3	EG	0.523581	0.472283	0.2676
	GF	-0.030556	0.145948	0.8342
	GPR	-0.046981	0.126925	0.7113
	GPP	-0.085583	0.188943	0.6506
	URB	-0.668429	2.032876	0.7423
0.3, 0.4	EG	0.036736	0.366949	0.9203
	GF	-0.044064	0.070451	0.5317
	GPR	-0.053016	0.042009	0.2069
	GPP	-0.044298	0.110472	0.6884
	URB	0.032899	0.237215	0.8897
0.4, 0.5	EG	0.007390	0.164855	0.9642
	GF	0.012465	0.036799	0.7348
	GPR	-0.042828	0.034903	0.2198
	GPP	0.043220	0.095325	0.6503
	URB	-0.112631	0.213013	0.5970
0.5, 0.6	EG	0.246889	0.191411	0.1971
	GF	0.025674	0.029194	0.3792
	GPR	-0.082269	0.042029	0.0503
	GPP	-0.079545	0.111371	0.4751
	URB	0.010745	0.238853	0.9641
0.6, 0.7	EG	0.388374	0.201075	0.0534
	GF	0.035601	0.027375	0.1934
	GPR	-0.106920	0.043651	0.0143
	GPP	-0.044635	0.116235	0.7010
	URB	0.175638	0.255867	0.4924
0.7, 0.8	EG	0.212596	0.191715	0.2675
	GF	0.009780	0.024878	0.6942
	GPR	-0.065768	0.041619	0.1141
	GPP	-0.070444	0.109092	0.5185
	URB	0.023230	0.275735	0.9329
0.8, 0.9	EG	0.143499	0.184279	0.4362
	GF	0.007716	0.024786	0.7556
	GPR	-0.020098	0.036908	0.5861
	GPP	0.129579	0.110910	0.2427
	URB	-0.325343	0.314536	0.3010

The results of the quantile slope equality test are given in Table 8, showing that the estimated impacts of all explanatory variables on carbon emissions are not homogeneous: values of the Wald test (Chi-Sq. = 183.54) are significant at a 1% significance level. This validates the use of the PQR approach to capture heterogeneous implications for determinants of carbon emissions among G7 countries. Among adjacent quantiles, variables have insignificant differences with high probability

values, indicating stable influences for multiple levels of carbon emissions. Valuable GPP differences between the 0.1 and 0.2 quantiles with significant p-values highlight that GPP has a higher emission-reducing role for lower emission levels. The GPR presented slope variations at Q0.50-Q0.70, highlighting that the influence of GPR becomes prominent at rising levels of emissions. Marginal variations were found for economic growth, depicting that the impact of economic growth on emissions varies at middle and high quantiles, while urbanization and green finance have comparatively consistent impacts across multiple levels of carbon emissions.

## 5. Conclusions and policy implications

The study investigated the empirical and heterogeneous impact of green finance, green production practices, geopolitical risks, economic growth, and urbanization on carbon emissions in G7 economies. Findings of IPS and ADF-Fisher unit root tests validate that all the variables were stationary at first difference. Outcomes of Johansen–Fisher and Kao cointegration tests confirmed the existence of a long-run stable equilibrium among variables. The study employed the panel quantile regression method to capture the varying implications of all explanatory variables on carbon emissions. Regression analysis showed a positive influence of economic growth on carbon emissions, which highlights how economic expansion leads to environmental degradation due to heavy reliance on traditional energy usage. However, the magnitude of coefficients showed a declining trend while moving from lower to upper quantiles, which depicted the adoption of environment-supportive measures with rising economic output. Green finance had a negative, significant effect on carbon emissions among all quantiles, highlighting the favorable environmental contribution of green financing due to shifting capital resources toward sustainable strategies. Geopolitical risks revealed a mixed (positive and negative) influence on carbon emissions. In lower quantiles, geopolitical risks showed a negative impact on emissions due to decreasing production activities, and a positive impact in the upper quantile due to increasing production based on energy-intensive methods. Additionally, green production practices had an environmentally supportive role through integrating environmentally friendly production measures and renewable energy sources. Rapid urbanization led to environmental degradation due to weak environmental regulations.

### 5.1. Policy suggestions

Based on the regression estimations obtained here, the following policy suggestions are proposed for G7 economies to enhance environmental quality (SDG-13).

- Governments of G7 nations should promote large-scale green industrial restructuring, emission efficiency standards, carbon pricing, renewable energy use, and transition of growth toward the low-carbon sector to reduce the adverse impact of economic growth (SDG-8) on carbon emissions.
- Policymakers should ensure green financing (SDG-12) for achieving environmental sustainability through climate-focused credit mechanisms, sustainable banking regulations, and public–private partnerships for ecologically efficient investments in G7 nations. On the other hand, the central banks can also play an important role in enhancing green finance for reducing CO<sub>2</sub> emissions.

- G7 policymakers should reduce geopolitical risks (SDG-16) and improve across-border cooperation for reducing uncertainties and financing energy-efficient methods of production to promote environmental quality.
- Governments of G7 should strengthen greener technology subsidies, green supply chains, and eco-innovation to enhance the favorable ecological role of green production practices (SDG-9).
- Policymakers should transition toward energy-efficient urban planning (SDG-11) by developing smart energy systems, mass public transport, urban green spaces, and green buildings, while ensuring environmental regulations.

## 5.2. Limitations of the study

Despite extensive empirical investigations, the study has the following limitations, which should be addressed in future research in the field of environmental sustainability:

- The study only focuses on G7 nations, which does not allow a generalization of the outcomes to other global regions, particularly in low-income and developing economies.
- The study uses a macro-level dataset, whereas sector-specific (industry, transport, and energy) environmental dynamics are ignored.
- The application of the panel quantile regression method captures efficient and heterogeneous linkages, however it does not estimate nonlinear relationships/thresholds caused by global shocks.

## Authors Contributions:

All authors contributed to the study's conception and design.

## Acknowledgements

This article is a part of activities funded by the Indonesian Endowment Fund for Education (LPDP) on behalf of the Indonesian Ministry of Higher Education, Science and Technology and managed under the EQUITY Program (Contract No. 4300/B3/DT.03.08/2025 and 297/UN3/HK.07.00/2025).

## Conflict of interest

The authors declare no competing interests.

## Ethics declarations

Not applicable.

## Ethical approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Data availability

All data generated or analyzed during this study are included in the published article.

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