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Effect of Environmental Taxes, Technological Innovation, and Green Energy on Environmental Degradation in G7 Countries: Insights from CS-ARDL and DCCE Model

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Abstract

This study investigates the influence of environmental taxes, technological innovation and green energy on the environmental degradation across G7 countries, between 2001 and 2023. For data analysis, the study utilized different econometric techniques including cross-sectional dependence, heterogeneity test, CIPS and CADF tests, the Westerlund test of cointegration, CS-ARDL model and DCCE model for robustness estimation. The findings show that environmental taxes, technological innovation and green energy are negatively and significantly linked to the CO2 emissions both in the short-run and in the long-run in G7 economies. Additionally, the study found a positive relationship between GDP and CO2 emissions, and a negative association between GDP2 and CO2 emissions thus validating the EKC hypothesis in G7 economies. The causality analysis shows that environmental taxes, technological innovation and CO2 emissions have a one-way causality whereas renewable energy and CO2 emissions have a two-way causality, which shows the interactivity of the clean energy transition. The results imply the need to incorporate fiscal instruments, technological advancement, and renewable energy plans to promote sustainable growth and climate goals in G7 economies.

Keywords Environmental Degradation, CO_2 Emissions, Environmental Taxes, Technological Innovation, Renewable Energy; G7 Countries; Environmental Kuznets Curve; CS-ARDL, DCCE Model.

INTRODUCTION

Environmental degradation is one of the warmest issues of the 21st century in the world. Environmental degradation is posing a threat to ecology, economies and health. It is a contributor to climate change, biodiversity loss and environmental insecurity through its rapid industrialization, deforestation, over exploitation of natural resources and augmented emission of greenhouse gases. They include a wide range of impacts, including food and meal shortages, health hazards, financial instability, and elevated levels of social disparities (Javed & Rapposelli, 2022; Ji et al., 2023). Environmental degradation is therefore a critical concern in the sustainable development and protection of the future generation. According to international organizations and researchers, policy intervention is urgently needed, a shift towards incorporating renewable energy, and technological advancement in order to diminish its impacts and promote environmental sustainability. One of the significant policy instruments governments have employed in addressing the environmental degradation issue is environmental taxation (ET). ET is commonly imposed on the use of energy or carbon emission or other types of pollutants and is an instrument to achieve externality costs of environmental degradation (Sterner & Köhlin, 2003; Ahmad et al., 2025). Well-designed environmental taxes and observed with transparent enforcement can lead to reduce CO_2 emissions (Andersson, 2019; Lin & Li, 2011). Although, ET effect can be differ in countries based on political will, administrative capacity, and complementary policies (Zenghelis, 2012).

According to Baumol and Oates (1988), pollution taxes internalize the external costs of pollution, making the pollution activities unattractive to the firms and households. European countries have experienced empirical evidence through a significant reduction in CO_2 emissions through recycling revenues gained through environmental taxes in green investments (Bosquet, 2000; Ekins, 1999). Parry et al., (2014) prove that carbon pricing policies, such as taxation, can cut off over 20 percent of emissions in high-income economies. However, such taxes are very delicate in their design since poor collection and government motivated exemptions can pose a weakness (Metcalf & Weisbach, 2009).

Technological innovation (TI) plays a dual role in shaping environmental degradation. On one hand, advancements in clean energy, green technologies, and digital solutions reduce carbon emissions, enhance resource efficiency, and mitigate ecological harm, thereby supporting sustainable development (Javed & Rapposelli, 2024). Conversely, innovation associated with industrial growth and energy-intensive manufacture may further raise pollution unless it is regulated by the environmental regulations (Abid et al., 2025). Therefore, the ecological consequences of technological change are based on policy frameworks, energy structures, and viable adoption routes.

Lastly, green energy (GE) is of utmost significance in minimizing the environmental degradation (ED) through decreasing greenhouse gases, reducing dependence on fossil fuels and improving the ecological sustainability (Sibt-e-Ali et al., 2024). It is not only supported by scholarly evidence but also indicates that the integration of GE can considerably enhance the environmental quality and sustainability outcomes (Iram et al., 2024; Zhu et al., 2024; Jiatong et al., 2023; Asghar et al., 2024). On the same note, it has been globally proven that renewable energy transitions lower emissions, promote energy security, and create green jobs and limit ED (Shen et al., 2024; Ameer et al., 2024). It is also observed that the use of renewable energy sources continuously reduces CO_2 emissions (CO_2E) in the short and long term (Sibt-e-Ali et al., 2023; Ji et al., 2023).

The G7 economies have a major challenge in environmental degradation despite their technological advancement and well-built institutions. The rise in GHS emissions, ecological imbalances, and resource depletion threaten the sustainability of the long-term and global climate goals (Zhao et al., 2023). Even though the purpose of environmental taxes is to internalize the cost of pollution, the environmental taxes effectively reduce emissions in other economies. Along the same line, technological innovation can potentially lead to cleaner production but unless it is channeled towards sustainability, it can lead to resource-intensive industrialization. Green energy adoption is generally regarded as a method of mitigation of environmental degradation, and its adoption and performance in G7 countries is not uniform due to policy, infrastructure, and market differences. To develop evidence-based policies, it is important to determine the effect of environmental taxes, TI and green energy on environmental degradation. Using the strong econometric models like CS-ARDL and DCCE provides a more insight on the short-run and long-run forces that enable G7 economies to balance between growth and environmental sustainability.

LITERATURE REVIEW

Environmental Taxes and CO_2 Emissions

Environmental tax is a policy instrument that has been extensively studied to reduce environmental degradation and there is much evidence that it is effective. Andersson (2019) provided one of the most cited ex-post evaluations and discovered that the carbon tax applied in 1991 in Sweden resulted in a significant reduction of CO_2 emissions without growing economy-wise. This fact is confirmed by cross-country research by Best et al., (2020) found that those countries which implemented carbon pricing experienced lower CO_2 growth rates and stronger tax rates that created more abatement effects. Similarly, Metcalf & Stock (2020) determined that European carbon taxes reduce emissions without macroeconomic consequences or with positive consequences. Study in the case of OECD economies also demonstrates that properly designed environmental taxes especially energy and pollution-related taxes play a vital role in reducing emissions (Al Shammre et al., 2023). Therefore, it is proposed that ET can reduce the CO_2 emissions.

Technological Innovation and Environmental Degradation

Technological change, particularly the development of low-carbon technology is one of the factors that play a critical role in environmental degradation. Innovation as Freeman & Soete (1997) suggested, enhances productivity and transforms the production in such a way that it becomes sustainable. In line with the above assertion, Jaffe et al., (2002) noted that induced technological change is one of the principal avenues of climate change mitigation since market signals about the price of energy encourage research and development (R&D) of cleaner alternatives (Huo et al.,2024; Basheer et al.,2024). Hall & Helmers (2013) have concluded that the patenting of renewable energy technologies saw an outstanding surge following international climate protocols, implying that the policy frameworks catalyze innovation. Furthermore, Lanjouw & Mody (1996) found that environment-friendly innovations migrated quickly in OECD countries, giving credit to the role of institutional quality on innovation. Study by Calel & Dechezleprtre (2016) also showed emissions trading schemes lead to innovations as they create an abatement technologies demand, again systemically supporting the relationship between policy and technological advances. Therefore, it is proposed that TI can have both positive and negative effects on CO_2E.

Green Energy and Environmental Degradation

The consumption of renewable energy has been always associated with the mitigation of CO_2 emissions. A study by Menyah & Wolde-Rufael (2010) conducted in the US indicated that the use of renewable energy does cut down the emissions in the long run, whereas the use of fossil fuels only increases them. Likewise, Omri & Nguyen (2014) found a high negative correlation between carbon emissions and renewable energy consumption among developed and emerging economies. According to Marques et al., (2010), policy frameworks are important in increasing the renewable energy shares in the domestic energy systems, especially the subsidies and feed-in tariffs. Moreover, a study by Sebri & Ben-Salha (2014) revealed data on the BRICS countries indicating that using renewable energy leads to positive results concerning sustainable and carbon-reducing development. Furthermore, Iram et al., (2024) found that green energy and ICT expenditures significantly reducing the environmental degradation in SAARC countries. Therefore, it is proposed that GE can reduce the CO_2 emissions in G7 countries.

DATA AND METHODOLOGY

This study analyzes the effect of environmental taxes, TI and green energy on environmental degradation in G7 (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) countries between 2001 and 2023. These economies are the pioneers to introduce environmental policy, approaches to technological innovation, and the switch to renewable sources of energy, a fact that makes them an appropriate setting to answer the question of long-term sustainability patterns. The data of CO_2E (metric tons per capita), GDP per capita, the number of patent applications to proxy technological innovation and consumption of renewable energy have been obtained through the World Development Indicators database of World Bank (Yin et al., 2025; Qadiret al.,2024).

The proportion of environmental tax revenue to GDP is based on data found in the OECD environmental statistics. The data was well balanced so that inconsistencies across the countries and even across the years were eliminated and the logarithmic transformations were made to the variables that have been found significantly skewed so that their variance was stabilized and the problem of heteroscedasticity was reduced to a minimum. To empirically test the impact of environmental taxes, TI and GE on ED, the study specifies the following model:

$$CO_2E_{it} = \beta_o + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 ET_{it} + \beta_4 GE_{it} + \beta_5 TI_{it} + u_{it}$$

Where CO_{2it} represents environmental degradation measured by carbon dioxide emissions for country *i* at time *t*. ET_{it} captures environmental taxes expressed as a percentage of GDP, TI_{it} reflects technological innovation proxied by the number of patent applications, and GE_{it} denotes renewable energy consumption as a percentage of total final energy use. Economic growth is represented by GDP per capita (GDP_{it}), while the squared term (GDP^2_{it}) is included to test the validity of the Environmental Kuznets Curve (EKC) hypothesis.

Econometric Strategy

The study employed different econometric methods for data analysis. The existence of the interdependence among the countries is determined using the cross-sectional dependence (CSD) test created by Pesaran (2015). To verify the compatibility of the parameters between countries, Pesaran & Yamagata (2008) test of slope homogeneity is applied. The second-generation unit root tests cross-sectional augmented Dickey-Fuller (CADF) and cross-sectional augmented Im-Pesaran-Shin (CIPS) tests are used to test the stationarity features of the variables. The tests have the right cross-sectional dependence and allow heterogeneity among countries. Westerlund (2007) proposes a panel cointegration test which estimates the existence of the long-run equilibrium of the used variables (Rasheed et al.,2024; Ayuningsih et al.,2024). In a study, estimations of the parameters are based on the cross-sectional augmented autoregressive distributed lag (CS-ARDL) model. This model offer useful estimations when working with mixed integration panels and can be applicable in both short and long run estimates. It takes into account the cross-heterogeneity and country-dependence, too. To ensure the power of the findings, the study also relies on the dynamic common correlated effects (DCCE) estimator which corrects the potential bias that may arise through unobserved common variables. Finally, a panel causality test introduced by Dumitrescu & Hurlin (2012) is carried out to examine the direction of causality between the variables.

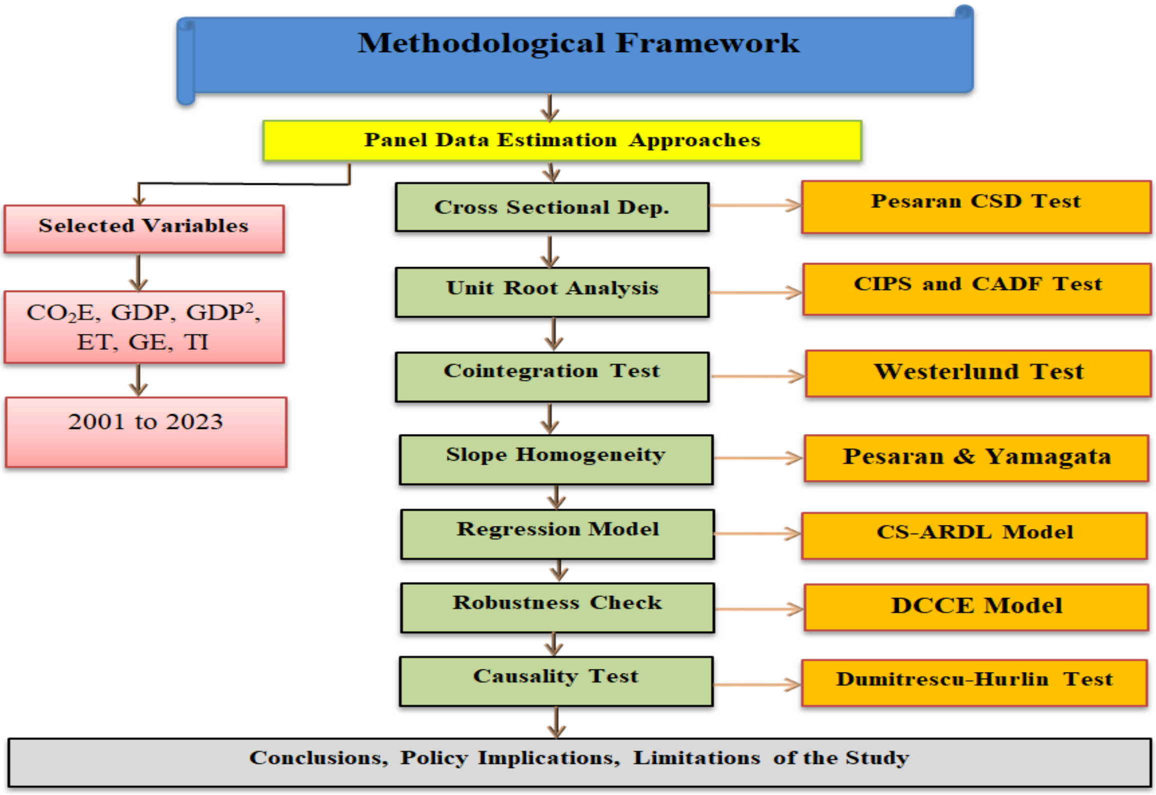

Figure 1.
Methodological Framework

DATA ANALYSIS

Descriptive Statistics

Table 1 presents the descriptive statistics of all the variables among the G7 countries between 2001 and 2023. The mean values of CO_2 emissions, ET, TI, GE and GDPPC in G7 countries are 11.84, 2.50, 18,754.22, 20.44 and 45,872.18, respectively. The minimum values of CO_2 emissions, ET, TI, GE and GDP in G7 countries are 4.02, 1.20, 2014, 6.12 and 27011, respectively. The maximum values of CO_2 emissions, ET, TI, GE and GDPPC in G7 countries are 19.89, 3.80, 34875, 34.55 and 63200, respectively.

Table 1.
Descriptive Statistics

Statistic	CO_2E	ET	TI	GE	GDP
Mean	11.84	2.50	18754.22	20.44	45872.18
Std. Dev.	4.53	0.79	8976.64	7.88	10144.61
Min	4.02	1.20	2014	6.12	27011
Max	19.89	3.80	34875	34.55	63200

Correlation Patterns

Table 2 presents the correlation matrix. The results show that CO_2E are negatively correlated with the environmental taxes (-0.42), technological innovation (TI), green energy (-0.46) while CO_2 emissions are positively correlated with the GDP per capita in G7 economies.

Table 2.
Correlation Matrix

Variable	CO_2E	ET	TI	GE	GDP
CO_2E	1.00	-			
ET	-0.42	1.00			
TI	-0.18	0.36	1.00		
GE	-0.46	0.44	0.29	1.00	
GDP	0.51	0.39	0.57	0.32	1.00

Cross-Sectional Dependence and Unit Root Properties

Table 3 demonstrates the outcomes of the Pesaran CSD test that shows that CSD statistic of all the variables is turn out to be statistically significant. This shows the high CSD among G7 countries (Li et al.,2024; Huo et al., 2024). These outcomes indicate that the variables CO_2 emissions, environmental taxes, technological innovation, green energy and GDP per capita are cross-sectionally dependent. Furthermore, the slope homogeneity test confirms the heterogeneity issue in a model.

Table 3.
Pesaran CSD Test Estimates

Variable	CADF Stat	P-Value
CO_2 Emissions	22.520***	0.000
Environmental Taxes	15.621***	0.001
Technological Innovation	18.489***	0.000
Green Energy	45.828***	0.000
GDP per capita	60.722***	0.000
Slope Homogeneity Test		
Test	**Statistic**	**P-Value**
Δ	15.288***	0.000
Δadj	19.725***	0.000

Note: **p<0.10, **p<0.05, ***p<0.01*

Table 4 presents the outcomes of CADF and CIPS unit root tests. The outcomes show that CO_2 emissions, technological innovation and GDP are found to be stationary at order one I(1) whereas environmental taxes and renewable energy are at a stationary level I(0). This combination of integration orders favours the use of the CS-ARDL model as it handles such situations (Mahmood et al.,2016).

Table 4.
Unit Root Tests (CADF & CIPS)

Variable	CADF Stat	CIPS Stat	Order
CO_2 Emissions	-2.15**	-2.34***	I(1)
Environmental Taxes	-4.32***	-3.95**	I(0)
Technological Innovation	-6.83***	-8.71***	I(1)
Green Energy	-3.97**	-4.02**	I(0)
GDP per capita	-2.05*	-2.18**	I(1)

Note: *p<0.10, **p<0.05, ***p<0.01

Cointegration Analysis

The outcomes of Westerlund cointgeration test is given in Table 5. The four statistics, G_t, G_a, P_t, and P_a, are all significant at the 1 percent level, which confirms the long-run cointegration between environmental taxes, technological innovation, GE, GDPPC and CO_2E in G7 countries.

Table 5.
Westerlund Panel Cointegration Test

Statistic	Value	Z-Value	P-Value
Gt	-3.72	-2.94	0.001
Ga	-15.11	-2.83	0.002
Pt	-9.42	-2.67	0.004
Pa	-12.08	-3.01	0.001

Long-Run and Short-Run Effects

The CS-ARDL outcomes for G7 economies in Table 6 reveal both long-run and short-run dynamics between ET, GE, TI, GDP and CO_2E. In the long run, environmental taxes significantly reduce environmental degradation *(coefficient = -0.21)*, suggesting that stringent tax policies effectively discourage environmentally harmful practices. Their short-run effect is also negative *(coefficient = -0.09)* but weaker, showing that taxes generate gradual improvements over time (also found by Al Shammre et al., 2023; Ahmad et al., 2025). Technological innovation play a significant role in the long-run *(coefficient = -0.12)*, where advances in cleaner production methods and energy efficiency help mitigate environmental degradation. However, the short-run impact is insignificant *(coefficient = -0.04)*, implying that the benefits of innovation materialize only after adoption and diffusion across industries (Abaidullah & Basheer, 2024; Basheer et al., 2024).

Green energy exhibits the strongest mitigating effect, both in the long-run *(coefficient = -0.34)* and short-run *(coefficient = -0.17)*, highlighting its critical role in the G7's transition toward low-carbon economies. This indicates that renewable energy adoption delivers immediate benefits while also ensuring sustainable long-term improvements in environmental quality (Basheer et al.,2024; Hassan, S. G, 2021). Regarding economic growth, GDP shows a positive effect on environmental degradation, meaning that expansion of economic activities increases ecological pressures. However, the negative and significant coefficients of GDP^2 confirm the Environmental Kuznets Curve (EKC) hypothesis for G7 economies. This suggests that growth initially worsens environmental outcomes beyond a certain threshold it fosters improvements through cleaner technologies, stricter regulations, and demand for sustainability (Asghar et al., 2024; Aydin et al., 2023).

Table 6.
CS-ARDL Long-Run and Short-Run Estimates in G7 Economies

Variable	Long-Run		Short-Run	
	Coefficient	t-Statistic	Coefficient	t-Statistic
Environmental Taxes	-0.21***	-3.84	-0.09*	-1.95
Technological Innovation	-0.12**	-2.44	-0.04	-0.88
Green Energy	-0.34***	-5.12	-0.17***	-3.01
GDP	0.45***	6.73	0.21***	3.42
GDP^2	-0.07***	-4.19	-0.03**	-2.27
ECT(-1)	--	--	-0.762***	-3.66

Note: *$p<0.10$, **$p<0.05$, ***$p<0.01$

Robustness Check

For the robustness estimation, this analysis used DCCE model. Table 7 shows that the variables environmental taxes, technological innovation and green energy are negatively and significantly affecting the CO_2E in G7 countries whereas GDP per capita is positively while square of GDPPC is negatively linked to the CO_2E in G7 economies validating the outcomes of CS-ARDL model.

Table 7.
Robustness Check (DCCE Model)

Variable	Coefficient	t-Statistic
Environmental Taxes	-0.19***	-3.54
Technological Innovation	-0.10**	-2.11
Green Energy	-0.32***	-4.85
GDP	0.48***	7.01
GDP^2	-0.06***	-3.77

Note: *p<0.10, **p<0.05, ***p<0.01

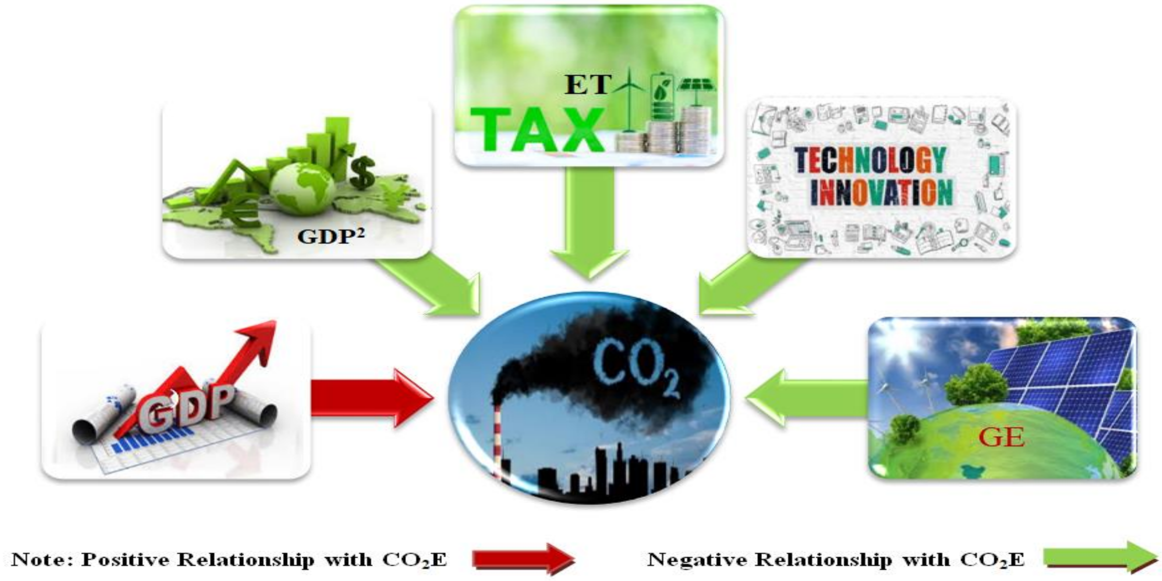

Figure 2.
Summary of CS-ARDL and DCCE Model Outcomes

Causality Analysis

Table 8 shows the result of the Dumitrescu-Hurlin causality test. The outcomes show that one-way causality is found between environmental taxes and CO_2E, TI and CO_2E, GDP and CO_2E. The study found two-way causality between GE and CO_2E in G7 countries.

Table 8.
Dumitrescu–Hurlin Panel Causality Test

Null Hypothesis	W-Stat	Zbar-Stat	P-Value	Result
ET → CO_2 (no causality)	4.12	2.84	0.004	Reject H_0
CO_2 → ET (no causality)	1.14	-0.62	0.534	Do not reject H_0
TI → CO_2 (no causality)	3.45	2.17	0.031	Reject H_0
CO_2 → TI (no causality)	0.94	-1.03	0.298	Do not reject H_0
GE ↔ CO_2 (no causality)	5.88	3.71	0.000	Bidirectional
GE ↔ CO_2 (no causality)	4.24	3.22	0.000	Bidirectional
GDP → CO_2 (no causality)	5.32	3.33	0.011	Reject H_0
CO_2 → GDP (no causality)	0.88	-1.23	0.149	Do not reject H_0

CONCLUSIONS

This paper analyzed the impacts of environmental taxes, technological innovation and green energy on CO_2E in the G7 countries from 2001 to 2023 through the application of different econometric models such as the CS-ARDL and DCCE. The evidence indicates that environmental taxes, technological innovation, and green energy adoption have a significant impact in the short and the long-term in terms of the reduction of CO_2E. Renewable energy is the most prominent of these, with very strong and consistent negative impacts on CO_2E. The application of environmental taxes too was efficient in discouraging the polluting culture and technological invention was an addition towards sustainability chiefly in the long-term. The results also confirmed the EKC in that, even though economic growth initially increases the intensity of emissions, growth in the higher levels of the economy eventually decreases the intensity of environmental degradation by implementing cleaner-improved technologies and stricter environmental controls. Causally, it was found that renewable energy is causally related to emissions and to the reduction in emissions, technology innovation and environmental taxes, which support its core contribution to sustainable development. Overall, the study provides strong empirical evidence that the integration of fiscal policies, technological progress and renewable energy is crucial in achieving climate goals. G7 countries must continue in improving these strategies in order to achieve long-term ecological balance and at the same time, continue to achieve economic growth.

IMPLICATIONS OF THE STUDY

The outcomes of this research have important policy and practical implications. Firstly, G7 governments should strive to determine the most appropriate way of designing and ensuring environmental taxes are effectively implemented in a manner that the funds can be recycled through transparent investment in green activities to attain the greatest environmental and economic benefits. Second, investing in clean and energy efficient technology, or technological innovation, in the long-term should be considered to achieve emission reductions in the long-term. Third, the process of switching to GE should be accelerated because it will provide both short-term and long-term benefits to the quality of the environment. Policymakers need to increase incentives, subsidies, and infrastructure building to aid the adoption of renewables. Lastly, since the EKC hypothesis holds, strategies must aim to push economies toward the turning point more quickly by combining strong regulations with green technology adoption, fostering sustainable growth trajectories.

LIMITATIONS OF THE STUDY

Despite its contributions, this study is not without limitations. First, the analysis is restricted to G7 countries, which may limit the generalizability of the findings to developing or emerging economies where institutional and policy frameworks differ. Second, while the econometric models employed address cross-sectional dependence and heterogeneity, unobserved factors like political dynamics, public resistance to taxation, and international environmental agreements may also influence outcomes but were not explicitly captured. Finally, technological innovation was proxied by patent applications, which may not fully represent practical implementation. Future research could expand the scope to more diverse economies and incorporate qualitative dimensions.

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