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RESEARCH ARTICLE

Realizing direct and indirect impact of environmental regulations on pollution: A path analysis approach to explore the mediating role of green innovation in G7 economies

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Abstract
The alarming impact of climate change and environmental pollutants has increased the focus of policymakers and think tanks' focus on formulating environmental regulations. Environmental regulations may reduce emissions directly and indirectly, as postulated by the famous Porter Hypothesis. It shows that environmental regulation may enhance pollution-reducing innovation by reducing agency costs while at the same time increasing firms' private benefit. The study is designed to investigate environmental regulations' direct and indirect impact on CO2 and GHG emissions using innovations as mediation factors. The study employs a structural equation method using data on G7 economies from 1990 to 2020 to test the relationship between regulations, innovations, and pollution. The study findings confirm that environmental regulations help reduce emissions directly. Our findings also confirm the Porter hypothesis whereby regulations encourage innovations and result in reduced emissions through this indirect channel. The study findings have significant implications for controlling pollution through placing environmental regulations and encouraging innovations.

Keywords Environmental regulations · Green innovations · Pollution · Structural equation model (SEM)

JEL Classification C33 · H23 · Q53 · Q55

Introduction

Global economic history has witnessed that environmental pollution in terms of global warming and the carbon cycle is the ultimate result of rapid economic growth (Wang et al. 2021b). For instance, countries have enjoyed phases of development at the cost of the environment. Likewise, it may not be possible to simultaneously achieve pollution reduction and sustainable management of resources (Wang and Song 2014). Negative externalities of economic development (carbon, chlorofluorocarbons, and other emissions) indicate the long-term nonexistence of environmental regulations. The G7 economies' industrial sectors do, however, make a sizable contribution to CO2 emissions, highlighting the necessity for strict environmental regulations. Production that is cleaner and more sustainable is still a major global problem. To reduce environmental pollution, such industrialized nations must abide by practical regulatory standards. However, most governments understand the risks of rising CO2 levels and are planning for climate-related events.

As a significant public hazard, environmental degradation has gained attention at the national level and alerted international bodies, comprising the Kyoto Protocol (KP) and Paris accord. These mentioned organizations are emphasized to embrace the policies that generate and boost economic significance (Porter and Kramer 2019). To attain sustainable environmental development, local administrators and governments embraced a set of environmental regulations, including pollution taxes (levies) and industrial-progress

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management leading to reduced emissions within their authorities (Ouyang et al. 2019). Environmental regulations directly improve environmental quality through pollution control equipment, taxes, and subsidies imposed on firms and perform more frequent maintenance. In addition, local officials directly blackout or transfer the unclean industry by using their influence over local land use (Massari and Monzini 2004).

With time, the importance of environmental regulation in solving the issues caused by economic activities has become a widely accepted notion (Blohmke et al. 2016; Yu et al. 2017). It is witnessed that environmental quality is deteriorating, and pollutants keep on increasing at the global level. The only solution is government policies regarding environmental regulations for developed and developing countries to overcome environmental pollutants (Chang and Wang 2010; Korhonen et al. 2015; Ouyang et al. 2019). Can developed countries' environmental regulations be strong enough to solve environmental problems effectively? Ecological regulations are categorized into administrative, market-oriented, and public contribution ecological regulation (Ren et al. 2018). Administrative ecological regulation deals with precautions, managerial policies, and orders to directly solve ecological problems. Market-oriented regulation increases the inherent power of enterprises designed by government units through market means (cost and price). Public participation in ecological regulation refers to the public interest through understanding and knowledge awareness to reduce environmental issues. Empirical findings are inconclusive in capturing the impact of environmental regulations on environmental quality. Some studies showed that environmental regulations could not achieve the expected effect of sustainable development by reducing pollution. For instance, Hao et al. (2018) did not find the expected impact of environmental regulation in improving environmental quality (low air pollution) by using a panel dataset of 283 cities in China from 2003 to 2021. Yuan et al. (2017) stated that the current environmental regulation level is insufficient to improve green efficiency. Moreover, firms' decision to flow government regulation policy depends primarily on environmental costs (Jaffe and Palmer 1997). Nevertheless, different regions have not experienced the same eco-friendly ecological impact through the implementation of different types of environmental regulations (Coxhead 2003; Solarin et al. 2021; Telle and Larsson 2007; Wang and Shen 2016; Zhao 2019).

Extensive research has focused on the direct impact of regulations on a sustainable environment (Chang and Wang 2010; Lin et al. 2021). However, environmental regulations may also indirectly affect the environment by promoting environmental innovations. Higher production costs caused by environmental regulations encourage innovation, as tight environmental regulations will force companies to invest in environmental protection technologies to reduce additional costs (Lin and Chen 2018). These processes will cause the improvement of low-pollution technologies to diminish pollution emissions (Wang et al. 2021a, b). Innovation caused by environmental regulation has a significant impact on environmental pollution. It is also a matter of whether green innovation leads to tight environmental standards. Also, we need to examine the role of green innovation in environmental issues.

Green innovation in reducing environmental pollution and attaining a sustainable environment has gained significant research consideration (Biondi et al. 2002; Nyiwul 2021; Pan et al. 2019; Su and Moaniba 2017). Green innovation is a comprehensive strategy to attain reasonable development. For example, it performs ecological protecting, energy saving, pollution averting, and waste recycling procedures (Albort-Morant et al. 2018). Green innovation can be classified into green marketing, management, and products. Innovation is termed green processes, management and competitiveness of firm, and providing a pollution-free environment (Seman et al. 2019). In contrast, pollution prevention explains the sustainable development of firms (Lin et al. 2021). These studies' results highlight innovation's prominence in attaining a sustainable environment (Li et al. 2019; Managi et al. 2021; Nill and Kemp 2009). Furthermore, the transformation of economic development through green innovation reduces environmental pollution. Many firms try to achieve better environmental and economic growth instantaneously (Dangelico and Pujari 2010). Since the 4th Industrial Revolution, the environment and innovative technologies have been interconnected megatrends (Gheraia et al. 2021).

CO2 emissions are a significant concern in the G7 countries. Figure 1 below presents the environmental pollution in terms of CO2 emissions of G7 countries from 1990 to 2020. The figure shows that the USA has the highest level of CO2 emissions throughout the selected years. At the same time, Canada has the lowest CO2 emissions as compared to other countries. It is essential to control the further deterioration of the environment in these countries for environmental sustainability and sustainable economic growth.

After adopting the Paris Climate Agreement (PCA) at COP21 in 2015, all G7 countries have worked toward a green, low-carbon future by diversifying their energy portfolios and using more renewable energy. G7 economies have yet to reduce CO2 emissions as these nations consume 30% of global energy and emit 25% of CO2 (World Bank 2022). For numerous reasons, we chose the G7 nations for analysis. First, the G7 economies, namely the US, Canada, UK, Germany, Italy, France, and Japan, are advanced economies with significant technology. Second, according to current research, these countries use one-third of the world's energy and emit the most carbon (Su et al. 2022). These statistics indicate why

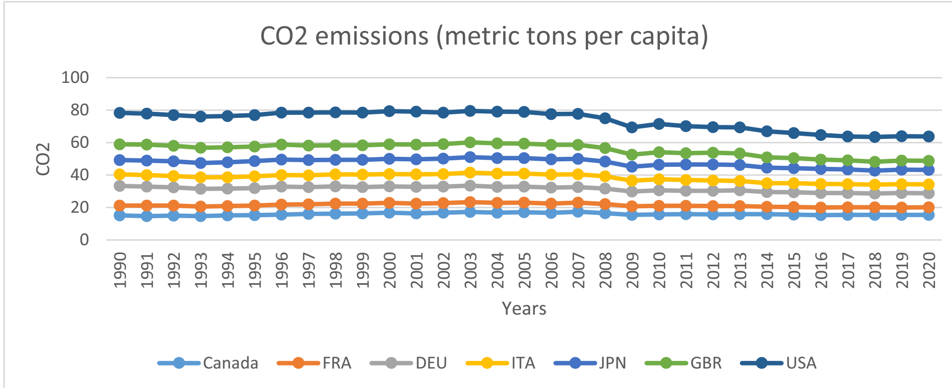

Fig. 1 CO2 emissions in G7 countries. Source: Author calculation

economically affluent nations cannot handle environmental degradation. G7 plans to deploy renewable energy to accomplish net-zero greenhouse gas emissions by 2050. Economic strength allows G7 nations to make the energy transition. In this regard, technology reduces CO2 emissions in these nations. The main objective of the current study is to analyze the direct impact of environmental regulations on the environment. Further, we have tested the indirect impact of regulations on environmental quality through the innovation channel.

This study examines the effect of environmental regulations on G7 renewable energy usage from 1990 to 2020. Structural equation modeling is used to explore the direct and indirect impact of environmental regulations on environmental issues and takes green innovations as a mediation variable. The control variables in the current analysis are urbanization, renewable energy consumption, industrial value added, GDP per capita, and school enrollment. Data availability determined the timeframe. The study reveals that environmental regulations directly reduce emissions. Our findings support the Porter hypothesis that regulations indirectly spur innovation and reduce emissions. The study findings have significant implications for pollution control through environmental regulations and innovation.

The further sections of the paper are designed as follows: "Literature review and theoretical derivation of hypothesis" Section presents the literature review and the theoretical relationship among environmental regulations, technological innovations, and sustainable environment. "Methodology and data" Section consists of the methodology and gives the detailed structure of the dataset used for the analysis. "Results and discussion" Section explains the estimated results, and "Conclusion" Section provides the concluding remarks with limitations and suggestions.

Literature review and theoretical derivation of hypothesis

Economies are facing severe environmental issues around the globe instead of implementing a series of regulations. However, environmental issues are worsening (Blohmke et al. 2016; Lin et al. 2021). Extreme environmental issues stimulated the responsiveness of society. They burden the government to implement environmental regulations (Lu et al. 2018) to reduce severe pollution behavior (Chen et al. 2018).

Doğan et al. (2022) examine the impact of environmental regulations in terms of tax on carbon emissions for the G7 nations from 1994 to 2014 and the influence of essential emissions drivers such as energy usage, economic complexity, natural resource rent, and economic development. The study also verifies the G7 Environmental Kuznets Curve Hypothesis and examines the marginal effects of an environmental tax on traditional energy consumption, natural resource rent, and renewable energy consumption. The results indicate that environmental taxes effectively reduce emissions for the G7 countries and confirm that the marginal effects of the environmental tax on traditional energy consumption, natural resource rent, and renewable energy consumption rise with taxation in a statistically significant way. Similarly, Safi et al. (2021) emphasize the environmental taxes and R&D on consumption-based carbon emissions in G7 countries from 1990 to 2019. The cointegration test shows a steady long-term relationship between environmental taxes, environmental R&D, imports, exports, GDP, and consumption-based CO2 emissions. Environmental taxes, R&D, and exports cut short- and long-term carbon emissions, whereas GDP and imports increase them. The Dumitrescu and Hurlin Granger causality test shows that environmental taxes, R&D, exports, imports, and GDP strongly affect CO2 emissions. Khan et al. (2020) employed the second-generation panel cointegration method to investigate the undiscovered factors accounting for G7 CO2 emissions from 1990 to 2017. Results indicate that imports and income increase consumer-based carbon emissions long-term, while exports, environmental innovation, and renewable energy usage reduce them.

In the case of higher clean production costs than environmental regulation costs, firms will keep the production techniques the same in order to get profits. The study found a positive relationship between environmental regulation and environmental pollution. Nevertheless, some studies conclude the desired impact of environmental regulation as He (2006) revealed that environmental regulations could reduce air pollution. Wang et al. (2011) concluded the Porter hypothesis that in case of higher environmental costs than clean production costs, firms would search for and familiarize new production techniques in Shandong, China, and ultimately sustainable environment can be achieved through environmental regulations.

Further, some economists concluded the inverted U-shaped relationship between regulation and ecological pollution (Li and Ramanathan 2018; Ouyang et al. 2019). With the rise in strict environmental policies, pollution emission increases and decreases as production capital needs time to adjust. Firms' reactions may need to be faster with low environmental regulations (Krysiak 2011), indicating the low cost of environmental regulation. On the other hand, with higher environmental regulation costs than clean production costs, firms' response is quicker.

Literature has witnessed that environmental regulation has ecological and economic effects, particularly in the labor market, as He et al. (2019) examine the environmental and economic effects of energy taxes charged in the four Nordic nations and the G7 countries from 1994 to 2016 using a panel ARDL model. Experiments reveal that the four Nordic countries and the G7 countries have found long-term green dividends: the Nordic countries reduce carbon dioxide emissions, while the G7 countries reduce fossil fuel use. Energy taxes in the four Nordic countries can lower distorted taxes, boost economic growth, and alter tax structures. Long-term G7 blue dividends are not reflected. The study uses a panel ARDL model for multi-country, multi-variable, and long-term cycle studies. Environmental regulations promote little technological progress, which leads to different employment demands (Curtis 2015). The heterogeneous nature of environmental regulation on employment has been observed, and new desires of the 1990 Air Act Amendments damaged the employment of thermal power plans (Sheriff et al. 2019). At the same time, Altman and Hunter (2015) found a positive impact of carbon-capturing projects on employment.

Another stream of literature postulates that the imposition of environmental regulation may promote innovation in the cleaning sector (Acemoglu et al. 2014). However, prerequisites are vital for innovation, to be exact, need to define certain environmental regulation levels. Environmental regulation is a vital cause of developing and creating green technologies, as tight environmental regulation leads to innovative research to adopt environment-friendly policies. Furthermore, in under-recognized settings of environmental regulations, innovations play a positive role in reducing pollution (Acemoglu et al. 2014). The environmental regulations may force high-polluting industries to adopt pollution control technologies, leading to research and development (Zhu and Ruth 2015). Strong countries like Japan, Germany, and the USA devote more consideration to environmental innovation—their innovation expenditures are more than pollution treatment (Lanjouw and Mody 1996).

Different environmental regulations impact green innovation performance, behavior, and intentions promoted with the market-incentive ecological regulations (Zhang et al. 2018). However, strong authorities can implement strict regulations to avoid "polluting the paradise" (Zeng and Zhao 2009). Literature has divided green innovation into two categories. First, green innovation is a firm's ability (Gluch et al. 2009), and second, green innovation is an administrative ecological practice (Lin et al. 2009). Organizational practices promote ecological and organizational performance and provide a competitive verge to firms (Rennings 2000). Another strand of literature considers green innovation as unique practices and processes, including technology and innovations, that ultimately benefit the environment and firms' sustainability (Ilvitskaya and Prihodko 2018; Xie et al. 2019).

Win–win situations can be achieved through environmental regulations (Chan et al. 2018) by achieving dual tasks, high profit, and lessening pollution. Applying green innovation is essential for economic and environmental goals through inside and outside implications of firms' restrictions (Saeed et al. 2018). For motivation and practicing green innovation, societal expectations and organizational support play vital roles (Shahzad et al. 2020). Moreover, Fernando et al. (2019) concluded that regulations, technology, and green innovations strongly impact sustainable performance through innovation capabilities. Ecologically friendly policies and practices directly and indirectly impact the environment (Famiyeh et al. 2018). Xie et al. (2019) did not find supportive results for green process innovation and organizational performance by using green innovation as a mediator.

Green innovation lies in the category of technological efficiency. Hence, relevant literature has linked environmental regulation with technological efficiency to explore the relationship between environmental regulation and green innovation. Neo-classical theories suggested that environmental regulation would cause an economic burden to firms, which ultimately raises the cost of production, which is unfavorable for firms to improve technological efficiency. At the same time, Porter's hypothesis suggests that environmental regulations enhance efficiency in technological innovations. Three aspects of literature have been formed; environmental regulation is helpful to promote technological efficiency, environmental regulation is not helpful to promote technological efficiency, and uncertainty prevails in attaining ecological regulation and technological innovation. The first aspect follows the Porter hypothesis, as Lanjouw and Mody (1996) found a positive impact of environmental regulation on environmental innovation in Japan, Germany, and the USA. Brunnermeier and Cohen (2003) and Jaffe and Palmer (1997) did similar work in the American manufacturing industry. The second aspect follows the neoclassical approach believing that high regulation puts economic pressure on firms in terms of the rising cost of production; ultimately, firms feel reluctant to spend on innovations (Gollop and Roberts 1983). The third aspect provided an inconsistent relationship between ecological regulations and innovations (Alpay et al. 2002; Li and Ramanathan 2018), as Lanoie et al. (2008) found inconsistent short-run and long-run impact of environmental regulation on manufacturing productivity in Canada.

Post-Paris climate agreement, many countries want to achieve carbon neutrality or zero carbon. Qin et al. (2021) study examine environmental policy, green innovation, composite risk index, and renewable energy R&D roles in G7 economies' 1990–2019 carbon neutrality targets. The G7 economies confirmed the EKC concept as environmental policy, green innovation, the composite risk index, and renewable energy R&D reduce carbon emissions. Income improves environmental degradation. Environmental policy, the composite risk index, green innovation, and CO2 emissions are all bidirectional, but GDP and renewable energy R&D are unidirectional. Literature has analyzed the direct impact of environmental regulation on green innovation through efficiency channels (Li et al. 2019). As neoclassical economists consider, environmental regulations increase production costs and burden initiators, discouraging enterprises from improving innovation efficiency, whereas (Porter 1991) believes that environmental regulation encourages enterprises to focus on innovations to reduce production costs. Similarly, the importance of technological and green innovations in achieving environmental protection has been widely recognized (Biondi et al. 2002; Chen et al. 2022; Lin et al. 2021; Managi et al. 2021; Su and Moaniba 2017). In short, a vast amount of literature has found the direct impact of regulations on the environment (Chan et al. 2018; Saeed et al. 2018; Shahzad et al. 2020), regulations on green innovations (Alpay et al. 2002; Brunnermeier and Cohen 2003; Jaffe and Palmer 1997; Lanjouw and Mody 1996; Lanoie et al. 2008; Li and Ramanathan 2018), and innovation on the environment (Albort-Morant et al. 2018; Biondi et al. 2002; Li et al. 2019; Managi et al. 2021; Nyiwul 2021; Pan et al. 2019; Seman et al. 2019; Su and Moaniba 2017). However, the impact of environmental regulations on sustainable development through green innovation channels is still dearth and matter to study. In addition, the current study contributes to the existing literature by introducing structural equation modeling. The current study examines the stimulus mechanism of environmental regulation, green innovation, and sustainable environmental progress.

Environmental regulations and pollution

Polluting industries can prosper from environmental regulations, claiming that effective environmental regulation can encourage innovation, which in turn raises production efficiency or product value for consumers, which is known as the Porter hypothesis. The direct impact of environmental regulations on ecological pollution can be captured in three ways. First, ecological regulations disrupt the constraints of reducing the cost of enterprises. Firms with higher costs will have more burdens and ultimately go bankrupt. This economic failure of pollution-intensive firms will lead to a lessening in general pollution emissions (Dey et al. 2018). Second, environmental regulation will pressure firms to familiarize themselves and use safe production techniques, reducing pollution and toxic emissions (Arouri et al. 2012). Third, environmental regulations will encourage the technological-based firm structure (Zeng et al. 2018), ultimately improving ecological progress with low emissions. Porter's hypothesis suggests relevant ecological regulations (Krysiak 2011). However, countries adopt different policies and environmental regulations (Lo et al. 2009) and developing areas. Countries may prefer economic growth at the cost of the environment, which will delay the regulation implementation process (Francesch-Huidobro et al. 2012). Nevertheless, it is wise to accept that sustainable ecological development is impossible with lower ecological regulations. With a certain level of environmental regulations, desired results will appear.

Hypothesis 1: In the presence of other things unchanged, environmental regulations reduce pollution levels.

Environmental regulations to innovations

Environmental regulation is a critical factor in implementing green innovations in the following facets. Porter hypothesis states the importance of environmental regulations in carrying out R & D, technical skills, competitions, and innovative skills (Porter and Linde 1995). Yang et al. (2012) consider that ecological regulations may boost innovation by enterprises through reimbursement outcome of innovation. Further, ecological regulations may guide innovation tactics (Yu et al. 2017). In the short term, ecological regulation will adversely influence enterprises while increasing firms' ecological protection capability and encouraging enterprises to promote innovations in the long run (Dechezleprêtre and Sato 2020). In short, ecological regulations promote R & D and promote green innovations.

Hypothesis 2: In the presence of other things unchanged, environmental regulations promote green innovation.

Green innovation to pollution

Environmental performance is assessed as a firm's performance in ecological and organizational betterment. Ecological performance encompasses less pollution, low carbon emissions, resource utilization, and improvement in energy savings (Zhu et al. 2010), indicating the firm's actions' effect on natural environs (Klassen and Whybark 1999). At the same time, organizational performance includes reputation, sale capacity, investor satisfaction, etc. (Venkatraman and Ramanujam 1986). Firms' supervisory processes and practices with effective resource utilization have a more powerful impact on long-term ecological impacts (Khan et al. 2019; Sarkis and Cordeiro 2001). Literature is witnessed that efficiency and betterment in the production process through research and development innovations may boost environmental performance (Montabon et al. 2007).

Green innovation includes innovation related to green products with energy saving, waste application, and toxic waste prevention (Chen et al. 2006). Stakeholder theory considers that contractors, consumers, and participants are the foremost powerful force for enterprises to innovate green (Fernando and Wah 2017). The institutional theory believes that the green innovation struggle results from the environmental regulations pressure of authorities on enterprises (Lin et al. 2014). Moreover, natural resource theory considers managers' administrative resources and significance vital to motivating enterprises to accomplish green innovations (Lin and Chen 2017). In short, green innovation boosts R&D investment and green technology, reducing pollution.

Hypothesis 3: In the presence of other things unchanged, green innovation reduces pollution. In light of the mentioned links, the current study explores the direct impact of environmental regulation on environmental quality and the indirect impact through green innovations as a mediator.

Methodology and data

Description and source of data

The objective of the current study is to find the direct and indirect impact of environmental regulation on environmental pollution through innovation channels in G7 countries. The G7 countries include Canada, France, Germany, Italy, Japan, the UK, and the USA. Panel data is taken from World Development Indicators (WDI) and OECD for 1990–2020. Table 1 presents the summary of variables used in the analysis.

Environmental pollution is an exogenous variable that is measured through CO2 emissions. Environmental regulation and innovation, as endogenous variables, are measured as environmental tax and patents, respectively. Control variables used in the analysis are as follows: Economic growth: when a country is experiencing the developing stage, the government ignores pollution to gain economic growth. After reaching the desired level of growth, people quest for a healthier life and environmental improvement (Strange 2006). Urban Population (UP): high urban Population indicates higher economic life in terms of industrial growth, which is associated with environmental pollution (Liu and Diamond 2005). School enrollment (SE) indicates individuals' responsive and positive attitudes toward environmental issues (Erhabor and Don 2016). Consumption of renewable energy (RE) helps improve environmental quality by reducing CO2 emissions (Boudri et al. 2002; Dincer 2000). A significant share of Industrial value addition (IV) causes

Table1 Description of variables

Variables	Units of variables	Source of data
Exogenous variables		
CO2 emissions	metric tons per capita	WDI (1990–2020)
Total greenhouse gas emissions	kilo tons of CO2 equivalent	WDI (1990–2020)
Endogenous variables		
Environmentally related taxes	% total tax revenue	OECD (1990–2020)
Environmental tax	Environmental-related total tax as a percent of GDP	OECD (1990–2020)
PATENT_ENV	Patent data present the percentage of attractive properties related to environmental technologies compared to other alternative innovation metrics	OECD (1990–2020)
Control variables		
Urban population	% of the total population	WDI (1990–2020)
Renewable energy consumption	(% of total final energy consumption	WDI (1990–2020)
Industrial value added	Industry (including construction), value added (% of GDP)	WDI (1990–2020)
GDP per capita	constant 2015 US$	WDI (1990–2020)
School enrollment, tertiary	(% gross)	WDI (1990–2020)

higher electricity generation, mining of coal, and burning of fossil fuels that lead to increased CO2 emissions (Wang et al. 2021a). The same mentioned variables influence the level of innovations; that is why the same control variables are used for innovations and pollution.

Table 2 indicates the summary statistics of variables with 217 observations used in the analysis. According to the observations, Table 2 highlights the countries and years of maximum and minimum values of mentioned variables.

Table 3 shows the correlation analysis. A negative correlation exists between environmental-related tax, environmental tax, and patent with environmental pollutants, CO2 emissions, and greenhouse gas emissions. Urban population, renewable energy consumption, industrial value, GDP per capita, and school enrollment positively correlate with CO2 emissions.

Pesaran (2015) test for weak cross-sectional dependence is applied to check for the dependence among cross sections. The null hypothesis of the test is that errors are

Table 2 Summary statistics of variables

Variables	Observations	Mean	Std. dev	Min	Max
CO2 emission	216	10.52629	4.478345	4.592377 France (2014)	20.47193 USA (2000)
Greenhouse gas emission	216	1,542,591	1,983,220	399,600 Italy (2018)	6,861,150 USA (2000)
Environmental related tax	216	5.751659	1.725348	2.78 USA (2015)	9.3 Italy (1995)
Environmental tax	216	1.50549	0.6665918	0.4480648 USA (2016)	3.006881 Italy (1995)
Patent	216	9.362366	2.765699	4.8 Italy (1992)	15.47 Germany (2011)
Urban population	216	77.94805	5.5714	66.706 Italy (1990)	91.782 Japan (2020)
Renewable energy consumption	216	9.390194	6.559564	0.6082641 UK (1991)	22.7699 Canada (2017)
Industrial value	216	24.4354	4.447301	16.44503 France (2020)	34.55387 Japan (1994)
GDP per capita	216	37,475.94	7378.243	27,479.58 Italy (1990)	60,836.77 USA (2019)
School enrollment	216	60.1008	14.56219	26.48239 UK (1990)	97.61021 Canada (1992)

Source: Author calculations.

Table 3 Correlation analysis of variables

	1	2	3	4	5	6	7	8	9	10
1	1									
2	0.720*	1								
3	−0.635*	−0.566*	1							
4	−0.690*	−0.705*	0.740*	1						
5	0.796*	0.818*	−0.692*	−0.705*	1					
6	0.449*	0.299*	−0.456*	−0.480*	0.378*	1				
7	0.035	−0.186*	−0.525*	−0.180*	−0.019	0.166	1			
8	0.269*	−0.013	0.097	−0.099	0.189*	−0.289	−0.143	1		
9	0.474*	0.596*	−0.587*	−0.580*	0.609*	0.305*	0.125	−0.518*	1	
10	0.495*	0.468*	−0.670*	−0.508*	0.491*	0.383*	0.453*	−0.429*	0.692*	1

* indicates the significance level 1% level.

1 = CO2 Emission, 2 = Greenhouse gas emission, 3 = Environmental related tax, 4 = Environmental tax, 5 = Patent, 6 = Urban population, 7 = Renewable energy consumption, 8 = Industrial value, 9 = GDP per capita. and 10 = School enrollment.

Source: Author calculations.

Table 4 Cross-sectional dependence

Variable	Statistics
Patent	4.33***
Environmental tax	12.38***
Environmental tax percent of total tax	15.5***
Urban population	−0.606
Renewable energy	20.76***
GDP per capita	21.53***
Industry value added	19.78***
Enrollment	10.6***
CO2 emissions	7.37***
GHG emissions	7.17***

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Source: Author calculations.

Table 5 Unit root testing (Pesaran panel unit root test)

Variables	Intercept and trend	
	I(0)	I(1)
Patent	−1.93	−5.11***
Environmental tax	−1.07	−4.22***
Environmental tax percent of total tax	−1.81	−4.76***
Urban population	−1.96	−4.92***
Renewable energy	−2.11	−5.77***
GDP per capita	−1.43	−3.87***
Industry value added	−2.01	−4.96***
Enrollment	−2.62	−3.28***
CO2 emissions	−2.24	−5.48***
GHG emissions	−2.15	−5.503***

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Source: Author calculations.

weakly cross-sectional dependent. The test statistics value for the overall model is 6.274, with a probability value of 0.0000. Hence, the hypothesis of cross-sectional dependence is rejected with a 99% confidence level. Table 4 below reports cross-sectional dependence test results for individual series. As we can see, we could not find enough evidence to accept the null hypothesis for the urban population. All other series show cross-section independence.

Next, a variance inflating factor (VIF) is applied to check the multicollinearity among the regressors. The mean VIF value is 4.03; below 10, multicollinearity among regressors is not detected. Table 5 reports the results from the unit root tests. All the series possess unit roots and become stationary after taking the first difference.

Graphical analysis

Figure 2 presents the graph of environmental patents among G7 countries. The figure indicates the mixed, overlapping, and upward trend with time. The highest patent trend is captured in Germany and the lowest in the USA.

Figure 3 indicates the environmental tax among G7 economies. Italy has practiced the highest environmental tax. At the same time, the lowest environmental tax is observed in the UK throughout the mentioned years.

In Fig. 4, the mix trend is observed in the case of environment-related tax. Comparatively, Italy has experienced the highest environment-related tax; the UK has a higher trend. At the same time, the UK has the relatively lowest level of environmental-related tax.

According to Fig. 5, the highest greenhouse gas emission is observed in the USA (6,000,000 kilo tonnes) from 1990 to 2020. At the same time, all other G7 countries have comparatively lower GHG emissions levels. Moreover, Italy has the lowest level of GHG emissions.

Overview of structural equation model

SEM indicates the causal association between latent and explicit variables through a generalized linear equation. Explicit variables may be termed measurable variables, which signify the objective and principal factors of the

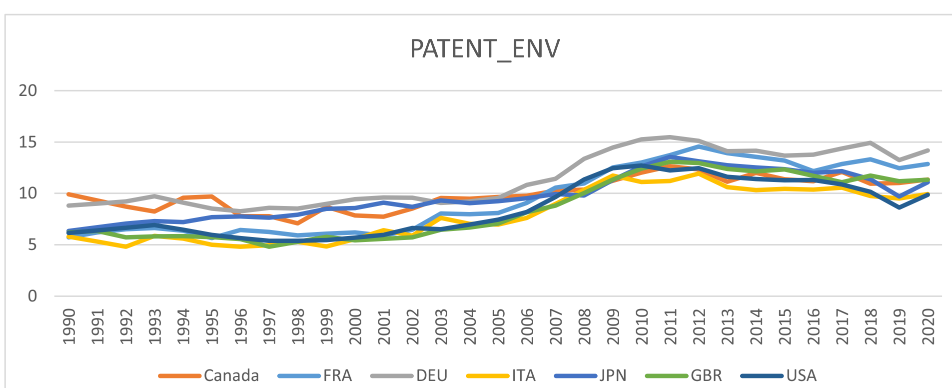

Fig. 2 Graphical analysis of patents in G7 countries. Source: Author calculation

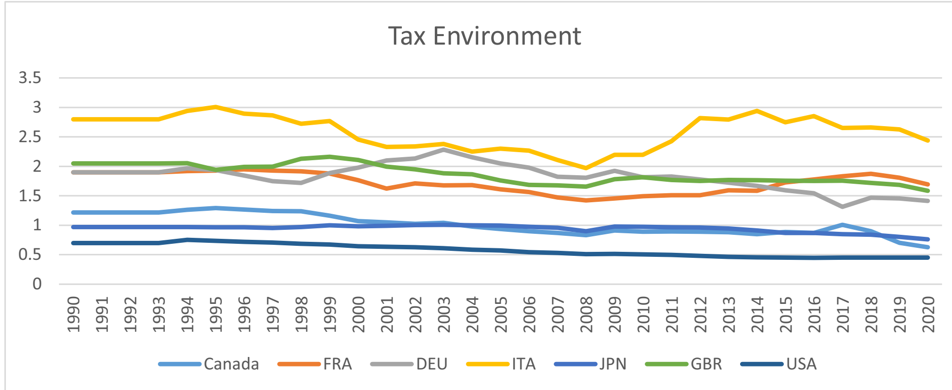

Fig. 3 Graphical analysis of tax environment in G7 countries. Source: Author calculation

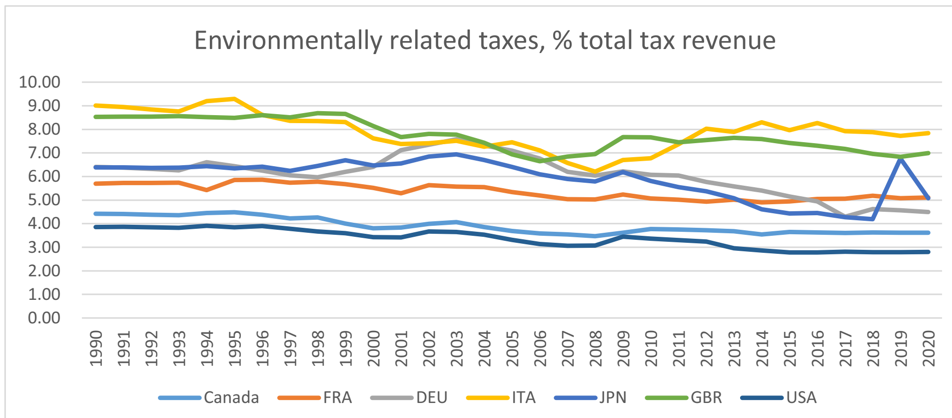

Fig. 4 Graphical analysis of environment related tax in G7 countries. Source: Author calculation

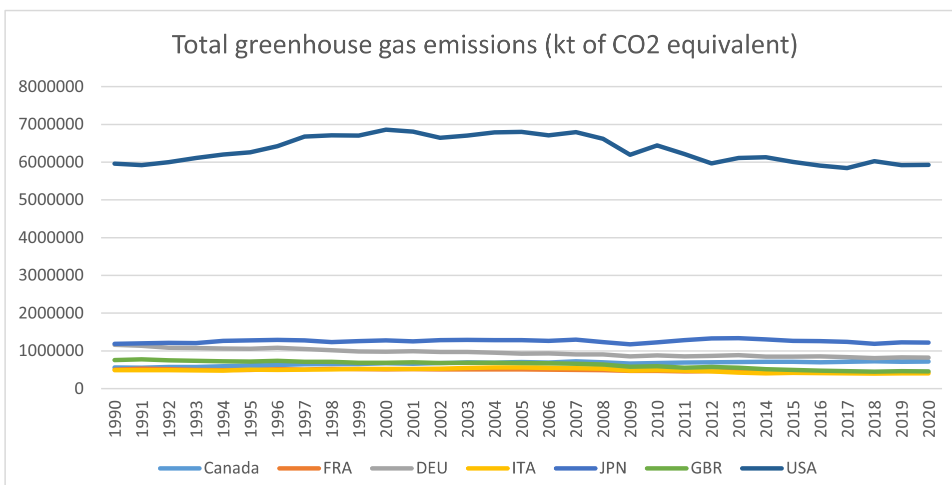

Fig. 5 Graphical analysis of GHG emissions in G7 countries. Source: Author calculation

analysis. Latent variables are unmeasured, as many variables cannot quantify in real life. The overview of latent variables is essential to specify the unquantifiable variables and to signify the latent aspects of the analysis object. In this way, the precision and comprehensiveness of the concrete analysis improve, which is the main objective of economic and social research. The structural equation model can present the concept of latent and explicit variables, which may be used to examine the unquantifiable variable model and investigate the endogeneity and probable path dependence. It explores linear causal links among variables while concurrently taking measurement error into account, making it similar to but more effective than regression analysis.

Following structural equation modeling, environmental regulation (ENRG), innovation (INNOV), and environmental pollution (CO2) are considered manifest variables. Among them, environmental regulation is an exogenous variable affecting pollution and innovations. Innovations are a mediation variable that affects pollution directly. However, environmental regulations affect both innovations and pollution. Henceforth, environmental regulations affect pollution directly and indirectly through their impact on innovations.

Environmental regulation is an exogenous variable that is measured through environmental taxes. Environmental pollution and innovation, as endogenous variables, are measured as CO2 emissions and patents, respectively. In the first part impact of environmental regulation is checked on pollution (CO2 emissions) and innovation (INNOV). Keeping the view of the literature, environmental regulation impacts innovation and pollution in mentioned ways. First, regulations encourage companies to invest in innovations to reduce costs.

Further, Porter's analysis suggests that the company will respond to environmental regulations to reduce pollution. Second, the environmental cost burden through strict environmental regulations discourages companies from improving environmental efficiency through innovations, presented by neoclassical economists. Additionally, the impact of innovations is checked on the pollution level of G7 countries. Green innovation in terms of R& D investment promotes green products with less toxic waste and energy saving benefits sustainable environmental growth with less CO2 emissions. Then direct and indirect impact is observed on the pollution level of G7 countries.

$$CO2_{it} = \alpha_0 + \alpha_1 ENRG_{it} + \alpha_2 INNOV_{it} + \alpha_3 UPOP_{it} + \alpha_4 RE_{it} + \alpha_5 GDP_{it} + \alpha_6 INDS_{it} + \alpha_7 ENRL_{it} + \varepsilon_{it} \quad (1)$$

$$INNOV_{it} = \beta_0 + \beta_1 ENRG_{it} + \beta_2 ETPT_{it} + \beta_3 UPOP_{it} + \beta_4 RE_{it} + \beta_5 GDP_{it} + \beta_6 INDS_{it} + \beta_7 IR_{it} + \varepsilon_{it} \quad (2)$$

Control variables used in the analysis are as follows: Economic growth (GDP): when a country is experiencing the developing stage, the government ignores pollution to gain economic growth. After reaching the desired level of growth, people quest for a healthier life to improve the environment (Strange 2006). Urban population (UPOP): high urban population indicates higher economic life in terms of industrial growth, which is associated with environmental pollution (Liu and Diamond 2005). School enrollment (ENRL) indicates individuals' responsive and positive attitudes toward environmental issues (Erhabor and Don 2016). Consumption of renewable energy (RE) helps improve environmental quality by reducing CO2 emissions (Boudri et al. 2002; Dincer 2000). A significant share of Industrial value addition (INDS) causes higher electricity generation, coal mining, and burning of fossil fuels that lead to increased CO2 emissions (Wang et al. 2021a, b). The same mentioned variables influence the level of innovations; that is why the same control variables are used for innovations and pollution. Panel data used for the current analysis are used for G7 countries, namely Canada, France, Germany, Italy, Japan, the UK, and the USA. Data is taken from World Development Indicators (WDI) and OECD for 1990–2020.

Since the series used in the analysis possess unit roots and become stationary at the first difference, the SEM analysis is conducted on the first-differenced series to account for the impact of unit root presence at the level. Furthermore, we have also applied SEM by adding panel fixed effects in the model. The results from fixed effects SEM are reported in Tables 14, 15, 16 and 17

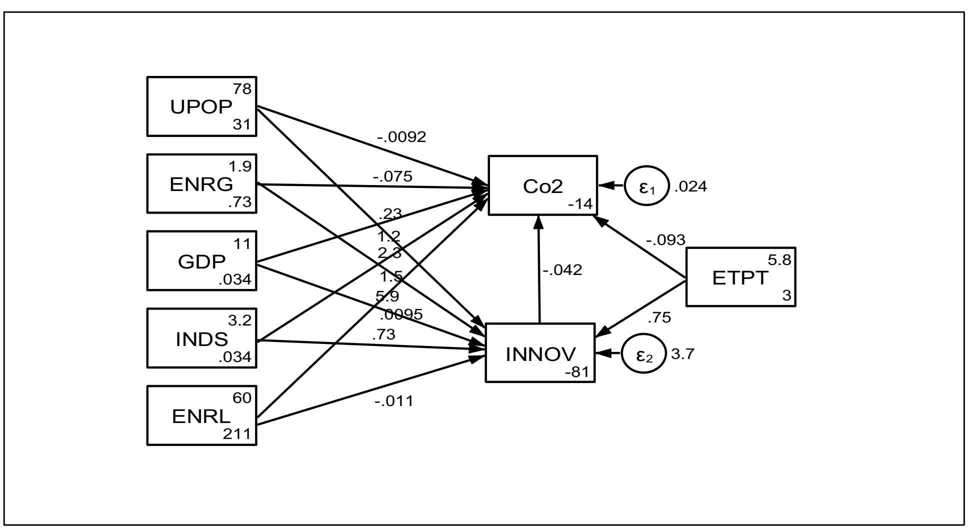

Fig. 6 Structural equation model of the impact of environmental regulations on CO2 emissions (environmental tax percent of total tax). Source: Author estimations

Results and discussion

This section presents the results from the structural equation model to test the direct and indirect impact of environmental regulations on CO2 emissions using innovations as a mediation variable. Figure 6 shows that the standardized path coefficient of innovations affecting CO2 emissions is – 0.042. The impact is significant, and the direction is unfavorable. The higher the innovations, the lower the level of CO2 emissions. This result confirms our hypothesis that higher innovations lead to lower emissions and supports the literature (Ilvitskaya and Prihodko 2018; Khan et al. 2019; Qin et al. 2021; Xie et al. 2019). The path coefficient of environmental taxes to CO2 emissions is – 0.093. The effect is significantly negative, confirming our hypothesis that higher regulations lead to lower emissions. This finding is consistent with the literature (Doğan et al. 2022; Qin et al. 2021; Safi et al. 2021). The path coefficient of ET to innovations is 0.75, which is positive and significant. It confirms our hypothesis that more environmental-related regulations lead

Table 6 Measuring the impact of environmental regulations on CO2 emissions (environmental tax percent of the total tax)

CO2 equation		Patents equation	
Patent → CO2	– 0.042***		
	(0.006)		
Environmental tax → CO2	– 0.093***	*Environmental tax → Patents*	0.755***
	(0.01)		0.152
Urban population → CO2	– 0.009***	*Urban population → Patents*	0.231***
	0.003		0.028
Renewable energy → CO2	– 0.075***	*Renewable energy → Patents*	2.345***
	0.021		0.207
GDP per capita → CO2	1.192***	*GDP per capita → Patents*	5.877***
	0.103		1.388
Industry value added → CO2	1.513***	*Industry value added → Patents*	0.735
	0.08		1.174
Enrollment → CO2	0.010***	*Enrollment → Patents*	– 0.011
	0.001		0.013
Constant	– 13.87***	*Constant*	– 81.02***
	1.233		17.892
Variance CO2	0.024***		
	0.002		
Variance e. patents	3.720***		
	0.293		
Equation-level goodness of fit			
mc(CO2)	0.93		
mc2(CO2)	0.85		
mc(Patent)	0.72		
mc2(Patent)	0.51		
R^2 *CO2*	0.86		
R^2 *2patent*	0.51		
R^2 *Overall*	0.93		
Observations	216		

Robust standard errors are in parentheses. The arrow sign represents the path direction. Renewable energy, urban population, GDP per capita, industry value added, and enrollment are used as control variables in both CO2 and patent equations as control variables. Environmental regulations are proxied by environmental-related tax as a percent of the total tax, and innovations are proxied by environmental-related patents. Mc = correlation between a dependent variable and its prediction. mc2 = mc^2 is the Bentler-Raykov squared multiple correlation coefficient.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: Author calculations.

Table 7 Direct and indirect effects of environmental regulation on CO2

Effects	Coefficient	OIM std. error	*z*	*P* > *z*	[95% conf	interval]
Direct effect						
Patents → CO2	−0.042	0.005	−7.620	0.000	−0.052	−0.031
Environmental tax → CO2	−0.093	0.012	−7.930	0.000	−0.116	−0.070
Environmental tax → Patent	0.755	0.137	5.520	0.000	0.486	1.023
Indirect effects						
Environmental tax → CO2	−0.031	0.007	−4.470	0.000	−0.045	−0.018
Total effects						
Patents → CO2	−0.042	0.005	−7.620	0.000	−0.052	−0.031
Environmental tax → CO2	−0.124	0.012	−10.050	0.000	−0.149	−0.100
Environmental tax → Patent	0.755	0.137	5.520	0.000	0.486	1.023

The effects are measured after estimating the structural equation of the impact of environmental regulations (measured as a ratio of environmental taxes to total taxes) on CO2 emissions using innovations (measured ad patents) as a mediation factor

Source: Author calculations.

to a higher level of innovation and supports the previous findings (Yu et al. 2017; Zeng et al. 2018). Table 6 presents the parameter estimation of the structural equation of the impact of ET on CO2 emissions.

Table 6 shows that the model fits well, and the coefficients confirm our tested hypothesis. Patents and environmental taxes significantly reduce CO2 emissions. Also, environmental taxes have a positive impact on patents. The coefficient is 0.75 and highly significant.

Table 7 presents the direct and indirect effects of the structural equation measured in Table 6. The direct and total effect of patents (innovations) on CO2 emissions is −0.042. The direct and total effect of environmental regulations on CO2 emissions is 0.75. In both cases, our hypothesis is confirmed that regulations and innovations significantly impact CO2 emissions.

The significant coefficient in this table is the indirect effect of taxes on CO2 emission through the channel of innovations. The indirect impact of environmental taxes on CO2 emissions is −0.03 leading to a total impact of −0.124. Henceforth, environmental taxes not only have a significant direct impact on CO2 emissions but also may influence emissions by encouraging innovations.

Next, we estimate the same structural equation by using greenhouse gas emissions to test the robustness of our estimates. Figure 7 presents environmental regulations' direct and indirect impact on GHG emissions using

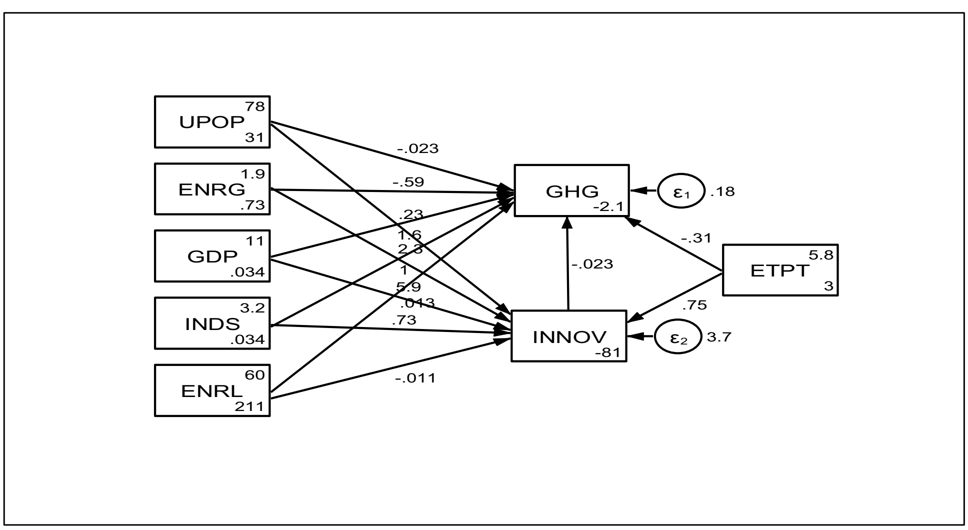

Fig. 7 Measuring the impact of environmental regulations on GHG emissions (environmental tax to total tax). Source: Author calculation

patents as a mediation variable. The path coefficient of taxes to GHG emissions is – 0.31, which confirms our hypothesis that taxes reduce emissions. The path coefficient of innovations to CO2 is – 0.023, implying that innovations lead to lower GHG emissions. The path coefficient of taxes to innovations is again 0.75, which explains taxes' highly significant and positive impact on innovations.

Table 8 presents the structural equation estimates to test the impact of environmental regulations on GHG emissions using patents as a mediation variable. Again, in this specification, regulations positively impact patents and, in turn, reduce GHG emissions in this specification.

Table 9 presents direct and indirect effects measured after the estimation of the structural equation model in Table 8. The direct impact of environmental taxes on emissions is – 0.313, which is highly significant. The indirect impact is – 0.017, and the total impact is – 0.33. Henceforth, environmental regulations not only have the potential to reduce emissions directly but also through their positive impact on innovations.

Furthermore, as a sensitivity analysis, both equations presented in Tables 6 and 8 are re-estimated using overall environmental taxes as a proxy for environmental regulations.

Table 8 Measuring the impact of environmental regulations on GHG emissions (environmental tax to total tax)

CO2 equation		Patents equation	
Patent → GHG	– 0.023*		
	– 0.012		
Environmental tax → GHG	– 0.31***	*Environmental tax → Patents*	0.755***
	– 0.03		– 0.152
Urban population → GHG	– 0.023***	*Urban population → Patents*	0.231***
	– 0.006		– 0.028
Renewable energy → GHG	– 0.590***	*Renewable energy → Patents*	2.345***
	– 0.059		– 0.207
GDP per capita → GHG	1.591***	*GDP per capita → Patents*	5.88***
	– 0.294		– 1.388
Industry value added → GHG	1.029***	*Industry value added → Patents*	0.735
	– 0.167		– 1.174
Enrollment → GHG	0.013***	*Enrollment → Patents*	– 0.011
	– 0.004		– 0.013
Constant	– 2.062	*Constant*	– 81.02***
	– 3.234		– 17.892
Variance GHG	0.184***		
	– 0.014		
Variance e. patents	3.720***		
	– 0.293		
Equation-level goodness of fit			
mc(GHG)	0.84		
mc2(GHG)	0.74		
mc(Patent)	0.71		
mc2(Patent)	0.51		
R^2 GHG	0.74		
R^2 Patent	0.51		
R^2 Overall	0.87		
Observations	216		

Robust standard errors are in parentheses. The arrow sign represents the path direction. Renewable energy, urban population, GDP per capita, industry value added, and enrollment are used as control variables in both CO2 and patent equations as control variables. Environmental regulations are proxied by environmental-related tax as a percent of the total tax, and innovations are proxied by the number of environmental-related patents. Mc = correlation between a dependent variable and its prediction. mc2 = mc^2 is the Bentler-Raykov squared multiple correlation coefficient.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: Author calculations.

Table 9 Direct and indirect effect of environmental regulation on GHGE (environmental tax to total tax)

Effects	Coefficient	OIM std. error	z	P > z	[95% conf	interval]
Direct effect						
Patents → GHG	− 0.022	0.012	− 1.83	0.067	− 0.047	0.002
Environmental tax → GHG	− 0.313	0.029	− 10.52	0.00	− 0.372	− 0.255
Environmental tax → Patents	0.754	0.152	4.96	0.00	0.456	1.052
Indirect effects						
Environmental tax → GHG	− 0.017	0.0095	− 1.8	0.072	− 0.036	0.001
Total effects						
Patents → GHG	− 0.022	0.012	− 1.83	0.067	− 0.047	0.002
Environmental tax → GHG	− 0.33	0.029	− 11.37	0.00	− 0.39	− 0.27
Environmental tax → Patent	0.75	0.152	4.96	0.00	0.456	1.053

The effects are measured after estimating the structural equation of the impact of environmental regulations (measured as a ratio of environmental taxes to total taxes) on GHG emissions using innovations (measured ad patents) as a mediation factor

Source: Author calculations.

Fig. 8 Structural equation model of the impact of environmental regulations on CO2 emissions (environmental taxes). Note: The effects are measured after estimating the structural equation of the impact of environmental regulations (measured as environmental-related taxes) on CO2 emissions using innovations (measured as patents) as a mediation factor

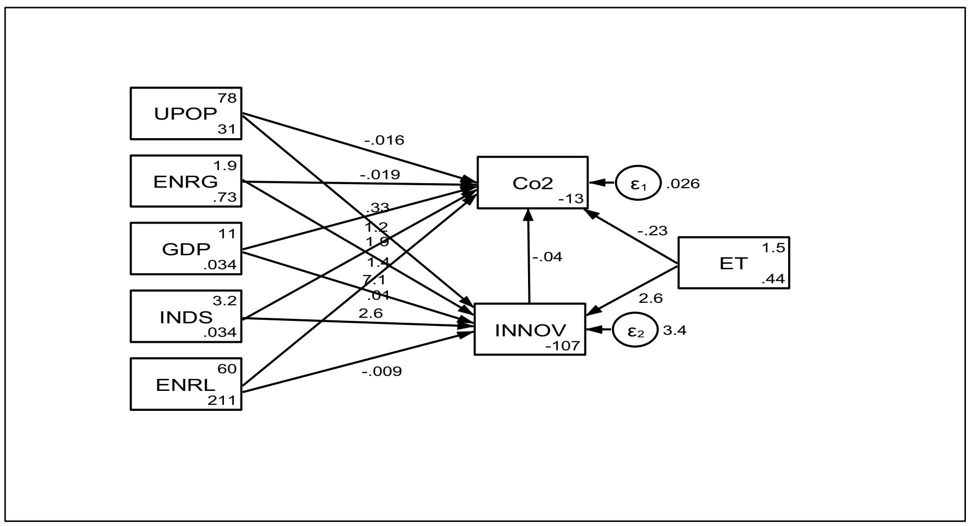

Fig. 9 Measuring the impact of environmental regulations on GHG emissions (environmental tax). Source: Author calculation

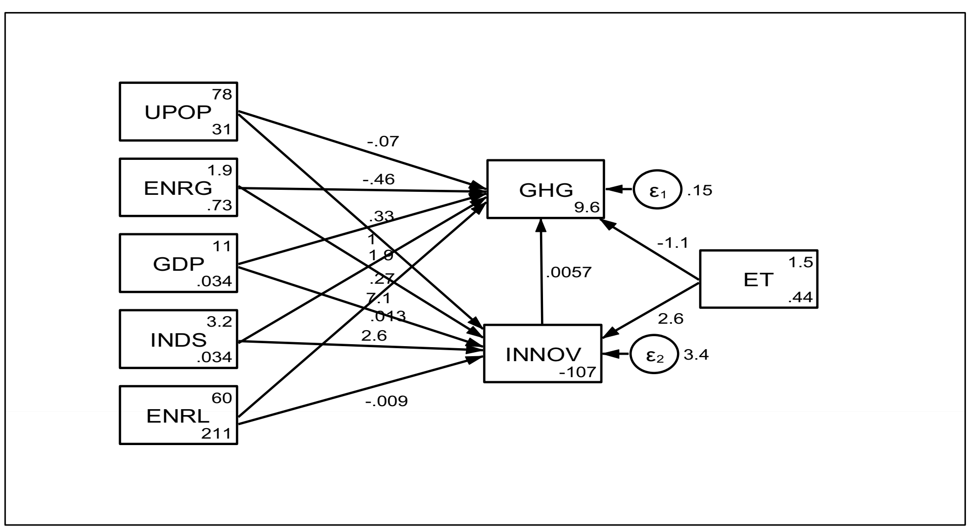

Table 10 Measuring the impact of environmental regulations on CO2 emissions (environmental tax)

CO2 equation		Patents equation	
Patent → CO2	− 0.040***		
	− 0.006		
Environmental tax → CO2	− 0.229***	*Environmental tax → Patents*	2.640***
	− 0.038		− 0.369
Urban population → CO2	− 0.016***	*Urban population → Patents*	0.332***
	− 0.004		− 0.028
Renewable energy → CO2	− 0.019	*Renewable energy → Patents*	1.925***
	− 0.022		− 0.161
GDP per capita → CO2	1.188***	*GDP per capita → Patents*	7.084***
	− 0.112		− 1.346
Industry value added → CO2	1.422***	*Industry value added → Patents*	2.640**
	− 0.082		− 1.282
Enrollment → CO2	0.010***	*Enrollment → Patents*	− 0.009
	− 0.001		− 0.012
Constant	− 13.331***	*Constant*	− 106.549***
	− 1.488		− 18.313
Variance CO2	0.026***		
	− 0.002		
Variance e. patents	3.434***		
	− 0.258		
Equation-level goodness of fit			
mc(CO2)	*0.92*		
mc2(CO2)	*0.85*		
mc(Patent)	*0.74*		
mc2(Patent)	*0.55*		
R^2 CO2	*0.85*		
R^2 Patent	*0.55*		
R^2 Overall	*0.93*		
Observations	*216*		

Robust standard errors are in parentheses. The arrow sign represents the path direction. Renewable energy, urban population, GDP per capita, industry value added, and enrollment are used as control variables in both CO2 and patent equations as control variables. Environmental regulations are proxied by environmental-related tax as a percent of the total tax, and innovations are proxied by the number of environmental-related patents. Mc = correlation between the dependent variable and its prediction. mc2 = mc^2 is the Bentler-Raykov squared multiple correlation coefficient.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: Author calculations.

Table 11 Direct and indirect effects of environmental regulation on CO2

Effects	Coefficient	OIM std. error	*z*	*P > z*	[95% conf	interval]
Direct effect						
Patents → CO2	− 0.040	0.006	− 6.59	0.000	− 0.052	− 0.028
Environmental tax → CO2	− 0.229	0.038	− 6.02	0.000	− 0.304	− 0.155
Environmental tax → Patent	2.640	0.369	7.150	0.000	1.917	3.364
Indirect effects						
Environmental tax → CO2	− 0.106	0.024	− 4.49	0.000	− 0.153	− 0.060
Total effects						
Patents → CO2	− 0.040	0.006	− 6.59	0.000	− 0.052	− 0.028
Environmental tax → CO2	− 0.335	0.040	− 8.43	0.000	− 0.413	− 0.257
Environmental tax → Patent	2.640	0.369	7.15	0.000	1.917	3.364

The effects are measured after estimating the structural equation of the impact of environmental regulations (measured as environmental-related taxes) on CO2 emissions using innovations (measured as patents) as a mediation factor

Source: Author calculations.

Table 12 Measuring the impact of environmental regulations on GHG emissions (environmental tax)

CO2 equation		Patents equation	
Patent → GHG	0.01		
	0.01		
Environmental tax → GHG	− 1.09***	*Environmental tax → Patents*	2.640***
	− 0.08		− 0.369
Urban population → GHG	− 0.070***	*Urban population → Patents*	0.332***
	− 0.01		− 0.028
Renewable energy → GHG	− 0.465***	*Renewable energy → Patents*	1.925***
	− 0.04		− 0.161
GDP per capita → GHG	1.000***	*GDP per capita → Patents*	7.084***
	− 0.31		− 1.346
Industry value added → GHG	0.27	*Industry value added → Patents*	2.640**
	− 0.18		− 1.282
Enrollment → GHG	0.013***	*Enrollment → Patents*	− 0.009
	0.00		− 0.012
Constant	9.581***	*Constant*	− 106.549***
	− 3.66		− 18.313
Variance GHG	0.149***		
	− 0.01		
Variance e. patents	3.434***		
	− 0.26		
Equation-level goodness of fit			
mc(GHG)	0.88		
mc2(GHG)	0.79		
mc(Patent)	0.74		
mc2(Patent)	0.55		
R^2 GHG	0.79		
R^2 Patent	0.55		
R^2 Overall	0.9		
Observations	216Rea		

Robust standard errors are in parentheses. The arrow sign represents the path direction. Renewable energy, urban population, GDP per capita, industry value added, and enrollment are used as control variables in both CO2 and patent equations as control variables. Environmental regulations are proxied by environmental-related tax as a percent of the total tax, and innovations are proxied by the number of environmental-related patents. Mc = correlation between the dependent variable and its prediction. mc2 = mc^2 is the Bentler-Raykov squared multiple correlation coefficient.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: Author calculations.

Table 13 Direct and indirect effects of environmental regulation on GHGE

Effects	Coefficient	OIM std. error	z	$P > z$	[95% conf	interval]
Direct effect						
Patents → GHG	0.0056	0.012	0.46	0.648	− 0.019	0.029
Environmental tax → GHG	− 1.099	− 13.12	0	− 1.264	− 0.935	− 0.255
Environmental tax → Patent	2.640	0.369	7.15	0.00	1.9167	3.364
Indirect effects						
Environmental tax → GHG	0.0149	0.033	0.45	0.65	− 0.049	0.0794
Total effects						
Patents → GHG	0.0057	0.076	− 14.41	0.00	− 1.232	− 0.937
Environmental tax → GHG	− 1.084	0.0291	− 11.37	0.00	− 0.387	− 0.273
Environmental tax → Patent	2.640	0.3691	7.15	0.00	1.917	3.364

The effects are measured after estimating the structural equation of the impact of environmental regulations (measured as environmental-related taxes) on GHG emissions using innovations (measured as patents) as a mediation factor

Source: Author calculations.

The hypothesis is confirmed and remains robust to this measurement change—Figs. 8 and 9 present the path coefficients of these estimations. Structural equation estimates and direct and indirect effects are reported in Tables 10, 11, 12 and 13. The results from fixed effects SEM (see Tables 14, 15, 16 and 17) confirm the findings obtained from SEM.

The study findings align with three critical streams of literature in the environmental and energy fields. Firstly, in line with the findings of the current study, it has been widely found in the literature that technological innovation is an important and valuable way to reduce environmental pollution and improve air quality (Grossman and Krueger 1995; Lin and Zhu 2019; Mol and Sonnenfeld 2000; Nyiwul 2021; Pan et al. 2019; Su and Moaniba 2017; Zhu et al. 2020). Moreover, these results highlight the importance of innovation for sustainable and green development (Kuhl et al. 2016; Kuzma et al. 2020; Li et al. 2019; Managi et al. 2021; Nill and Kemp 2009; Schiederig et al. 2012). Technological and managerial innovation are the two most significant factors in achieving environmental sustainability (Biondi et al. 2002). Extant research has indicated that most pollution reductions in the USA have come from technological changes rather than any changes in imports or goods produced domestically (Levinson 2009).

Secondly, the study has found a significant impact of environmental regulations on environmental performance. Environmental regulation is believed to be an effective tool for solving the environmental problems caused by economic activities and energy consumption (Blohmke et al. 2016; Yu et al. 2017). Environmental regulation can affect environmental problems and economic activities, eventually changing the labor market (Liu et al. 2017). Stick environmental regulation will increase polluting enterprises' costs (Dey et al. 2018; Ramos et al. 2018). Therefore, these companies will invest in environmental protection technologies to reduce extra costs (Lin and Chen 2018).

Thirdly, we have found a positive impact of regulations on innovations, thereby confirming the Porter hypothesis. Neoclassical economic theorists believed that environmental regulation would bring an economic burden to enterprises, resulting in increased production costs, which could have been more conducive to improving technical efficiency. However, Porter (1991) held that environmental regulation could promote the technological innovation of enterprises and then improve technical efficiency, which was called the "Porter Hypothesis." Hence, the study has established a direct and indirect link between environmental regulations with environmental performance using innovations as a mediation channel.

Conclusion

This study has examined environmental regulations' direct and indirect impact on environmental performance using innovations as a mediatory factor. The study employed the structural equation method using data on G7 economies from 1990 to 2020 to test the relationship between regulations, innovations, and pollution. Based on these empirical findings, this paper recommends the following policy changes. Environmental taxes should be used to control carbon emissions directly and mediate other key carbon emissions determinants, such as green innovations. To create a new long-term green economy equilibrium, the G7 governments should tax fossil fuels to take advantage of the pandemic's market instability. The pollution taxes that push enterprises toward adopting cleaner production must be imposed. A set of incentives and punishments is devised whereby financial subsidies and incentives are provided to those with cleaner production, and penalties are implemented on enterprises making severe pollution emissions.

In addition to improving climate welfare, the economy is impacted by implementing an environmental tax (carbon tax) in other ways. Due to high prices that limit consumer spending due to an increase in cost, businesses may be unable to invest as much money as they would want in technology that reduces emissions. A carbon tax provides economic benefits beyond climate welfare. The carbon tax raises prices, which reduces consumer spending and may limit industry investments in emission-reducing technology. Environmental regulations are found to directly and indirectly, impact environmental performance through innovation. Therefore, governments must devise and implement environmental regulations wisely up to a specific limit which helps reduce CO2 emissions and raise innovation. Next, we suggest combining a variety of environmental regulation measures to achieve maximum benefit from them. Finally, the governments must provide awareness and information to residents and enterprises to improve the use of clean energy and develop a green economy. By developing a policy stimulus for renewable energy, the cash from the carbon tax should be directed to citizens' welfare, as in the case of the US economy. Green jobs can also be created with the help of this stimulus.

This research could be expanded to include the OECD or G20 panel observations. Second, the country-level analysis would show how environmental taxes affect each nation's uniqueness. Finally, extensive research on the effects of environmental taxes on other polluting variables outside carbon emissions could add to the literature.

Appendix Robustness analysis using panel fixed effects in SEM framework

Table 14 Measuring impact of environmental regulations on CO2 emissions (environmental tax per cent of total tax)

CO2 equation		Patents equation	
Patents → CO2	−0.742***		
	(0.0651)		
Environmental tax → CO2	−0.021	*Environmental tax → Patents*	0.742***
	(0.11)		0.065
Urban population → CO2	0.099	*Urban population → Patents*	−0.021
	(0.021)		0.113
Renewable energy → CO2	−0.169***	*Renewable energy → Patents*	0.100***
	0.0257		0.025
GDP per capita → CO2	0.34***	*GDP per capita → Patents*	0.788***
	0.037		0.100
Industry value added → CO2	0.787***	*Industry value added → Patents*	−0.169***
	0.099		0.021
Enrollment → CO2	0.0259	*Enrollment → Patents*	0.340***
	0.038		0.038
Constant	−5.866***	*Constant*	−8.758***
	1.734		1.67
Variance CO2	0.024***	*Variance FE*	*0.978*
	0.002		*0.28*
Variance e. patents	3.720***	*Variance ERR1*	*0.96*
	0.293		*0.26*
cov(Environmental tax, FE)	−0.0001***		
cov(Urban population, FE)	−0.0001***		
cov(Industry value added, FE)	0.0022***		
cov(Renewable energy, FE)	−0.0007***		
cov(GDP per capita, FE)	0.0000***		
Cov(Enrollment, FE)	−0.0236***		
Observations	217		

The model is estimated through SEM using panel fixed effects. Standard errors are in parenthesis.

FE fixed effects.

*, **, *** Significance level at 90%, 95%, and 99% level

Source: Author calculations.

Table 15 Measuring impact of environmental regulations on GHG emissions (environmental tax per cent of total tax)

CO2 equation		Patents equation	
Patent → CO2	− 0.178***		
	0.013		
Environmental tax → CO2	− 0.276***	*Environmental tax → Patents*	0.378**
	0.113		0.0112
Urban population → CO2	0.125***	*Urban population → Patents*	0.276*
	0.016		0.142
Renewable energy → CO2	1.126***	*Renewable energy → Patents*	0.023
	0.038		0.032
GDP per capita → CO2	− 0.017***	*GDP per capita → Patents*	1.126***
	0.004		0.038
Industry value added → CO2	0.023	*Industry value added → Patents*	0.125***
	0.032		0.016
Enrollment → CO2	− 0.043***	*Enrollment → Patents*	− 0.017***
	0.007		0.004
Constant	14.82***	*Constant*	− 4.306***
	1.060		1.67
Variance CO2	− 0.124	*Variance FE*	*1.45*
	0.002		*0.21*
Variance e. patents	1.720***	*Variance ERR1*	*0.82*
	0.0293		*0.02*
cov(Environmental Tax, FE)	− 0.660***		
cov(Urban population, FE)	− 0.052		
cov(Industry value added, FE)	0.012***		
cov(Renewable energy, FE)	− 0.497***		
cov(GDP per capita, FE)	0.058***		
cov(Enrollment, FE)	7.754*		
Observations	217		

The model is estimated through SEM using panel fixed effects. Standard errors are in parenthesis.

FE fixed effects.

*, **, *** Significance level at 90%, 95%, and 99% level

Source: Author calculations.

Table 16 Measuring impact of environmental regulations on CO2 emissions (environmental tax)

CO2 equation		Patents equation	
Patent → CO2	−0.66***		
	0.07		
Environmental tax → CO2	0.09	*Environmental tax → Patents*	0.66***
	0.12		0.08
Urban population → CO2	0.15***	*Urban population → Patents*	0.09
	0.02		0.12
Renewable energy → CO2	−0.16***	*Renewable energy → Patents*	0.15***
	0.03		0.02
GDP per capita → CO2	0.34***	*GDP per capita → Patents*	1.33***
	0.04		0.12
Industry value added → CO2	1.33***	*Industry value added → Patents*	−0.16***
	0.12		0.03
Enrollment → CO2	0.02	*Enrollment → Patents*	0.35***
	0.04		0.06
Constant	−7.51***	*Constant*	−21.39***
	1.73		1.67
Variance CO2	−0.003	*Variance FE*	*0.998*
	0.002		*0.28*
Variance e. patents	0.186	*Variance ERR1*	*0.96*
	0.132		*0.26*
cov(Environmental tax, FE)	−0.0003		
cov(Urban population, FE)	−0.0003		
cov(Industry value added, FE)	0.0023		
cov(Renewable energy, FE)	−0.0007		
cov(GDP per capita, FE)	0.0000		
cov(Enrollment, FE)	−0.0135		
Observations	217		

The model is estimated through SEM using panel fixed effects. Standard errors are in parenthesis.

FE fixed effects.

*, **, *** Significance level at 90%, 95%, and 99% level

Source: Author calculations.

Table 17 Measuring impact of environmental regulations on GHG emissions (environmental tax)

CO2 equation		Patents equation	
Patent → CO2	−0.258		
	0.128		
Environmental tax → CO2	−0.742***	*Environmental tax → Patents*	0.732**
	0.207		0.128
Urban population → CO2	0.208***	*Urban population → Patents*	0.543**
	0.050		0.207
Renewable Energy → CO2	0.013	*Renewable energy → Patents*	0.108***
	0.054		0.040
GDP per Capita → CO2	0.035***	*GDP per capita → Patents*	1.331***
	0.014		0.120
Industry value added → CO2	1.567***	*Industry value added → Patents*	−0.156***
	0.213		0.032
Enrollment → CO2	0.035***	*Enrollment → Patents*	1.567***
	0.014		0.025
Constant	9.202***	*Constant*	−15.19***
	1.734		3.450
Variance CO2	−0.0009	*Variance FE*	*1.400*
	0.002		*0.280*
Variance e. patents	0.887	*Variance ERR1*	*0.820*
	0.191		*0.260*
cov(Environmental tax, FE)	−0.564		***
cov(Urban population, FE)	0.115		***
cov(Industry value added, FE)	−0.7746		
cov(Renewable energy, FE)	−0.5721		***
cov(GDP per capitA, FE)	0.151		***
cov(Enrollment, FE)	6.759		***
Observations	217		

The model is estimated through SEM using panel fixed effects. Standard errors are in parenthesis.

FE fixed effects.

*, **, *** Significance level at 90%, 95%, and 99% level

Source: Author calculations.

Author contribution **RN:** Conceptualization, writing—original draft, formal analysis, data handling, and methodology. **SG:** Supervision, write-up. **MNS:** Writing—review and editing, variable construction.

Data availability All data generated or analyzed during this study will be available at appropriate demand.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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