

## RESEARCH ARTICLE

# Do Patents on Environmental Technologies Truly Facilitate the Green Transition in Japan? A Pathway to the 2050 Net-Zero Emission Target

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## ABSTRACT

In the context of the Paris Agreement, many governments have been tackling climate change and trying to achieve net-zero emission targets by 2050, since these targets are vital to limiting global warming to 2°C for a sustainable planet. This study explores the linkage between environmental sustainability and environmental patents in Japan. For this purpose, the study covers 1975–2021 and employs novel econometric approaches such as the Fourier unit root, Fourier ARDL cointegration, and Fourier-based long-term coefficient techniques. As a result of the empirical findings, we first capture a long-run cointegration relationship between environmental sustainability, environmental patents, economic growth, and energy consumption. We unexpectedly discovered empirical evidence that contradicts the existing literature. According to the Fourier-based long-term coefficient results, environmental patents, economic growth, and energy consumption adversely affect environmental quality. Therefore, we have three main interpretations of the findings. (i) Contrary to expectations, patents on environmental technologies adversely impact environmental sustainability. (ii) Japan has not yet achieved a decoupling between economic growth and CO<sub>2</sub> emissions. (iii) The negative impact of environmental patents on environmental sustainability reveals that environmental patents have yet to have any influential power in achieving net-zero emission targets. In addition, environmental patent strategies do not help emission reduction in Japan. Therefore, if policymakers emphasize long-term environmental patent policies, they might establish an additional strategy to achieve net-zero targets, which is crucial for mitigating possible emission gaps. These findings suggest that Japanese policymakers should support effective environmental patents to achieve the net-zero emission target by 2050.

## 1 | Introduction

Many countries have been attempting to mitigate the current and future consequences of climate change and environmental pollution. To this end, governments implement various policies and establish new projects aimed at reducing environmental pollution, emissions, and ecological footprints. The priority in combating environmental pollution is to reduce energy consumption derived from fossil fuels and utilize clean energy sources. However, in numerous countries, fossil fuels remain

the dominant energy source. Approximately 84% of the primary energy consumed globally came from fossil fuels during the period from 1965 to 2020 (Statista 2023). Although the share of fossil fuels has fallen due to renewable energy, they are still responsible for the lion's share of energy consumption. Therefore, countries should not neglect sustainable development and green transition policies. In this context, the United Nations Framework Convention on Climate Change (UNFCCC) tries to strengthen the fight against climate change by bringing governments together at the Conference of the Parties (COP) meetings.

Attaining the sustainable development goals (SDGs) set forth by the UN is another vital strategy. These goals are based on improvements in many areas, such as environment, energy, education, health, democracy, poverty, infrastructure, and equality. The barrier to sustainable development is that the biggest trigger of sustainable development is economic growth, which is mainly fed by fossil fuels. In this sense, many developed countries have been trying to achieve decoupling, which means decomposing economic growth from emissions. As the economy grows, energy consumption might decrease, and environmental quality will improve. Another critical challenge regarding climate change is the 2050 net-zero emission targets committed by many countries within the framework of the Paris Agreement. Achieving net-zero emission targets will undoubtedly support emission mitigation and will be essential in climate change efforts. However, many studies claim that it is necessary to go beyond the net-zero emission target for a sustainable earth (Höhne et al. 2021; Meinshausen et al. 2022; Ou et al. 2021).

Every country strives to the extent of its ability to combat environmental pollution and climate change. However, regardless of the income group (underdeveloped/developing/developed), the prerequisite for almost every country is not to compromise on economic growth. Since economic activities are based on energy consumption and energy consumption is mainly met by fossil fuels, economic growth triggers energy consumption and environmental pollution. According to the International Energy Agency (2022), to limit global warming at 1.5°C, coal and natural gas should be eliminated from our energy production by 2040 and switched to renewable energy sources such as solar, wind, hydroelectric, and nuclear. The support of technology is essential to achieve these goals. Technological development changes production techniques and consumption patterns, and thus affects environmental sustainability. In the Environmental Kuznets Curve, “scale effect, composition effect, and technical effect” are essential factors (Grossman and Krueger 1991). In the early stages of economic development, countries generally ignore environmental quality to increase production. At this stage, the scale effect is more dominant, which means environmental degradation increases with income levels. However, at the next stage, individuals pressure governments to improve environmental quality. Thus, the composition effect emerges, and more environmentally friendly products begin to be produced. Finally, technology transfer resulting from trade liberalization and foreign direct investments improves environmental pollution, especially in underdeveloped and developing countries. In addition, artificial products are produced instead of natural resources, and environmental waste is disposed of in a way that is less harmful to nature. This progress is called the technical effect.

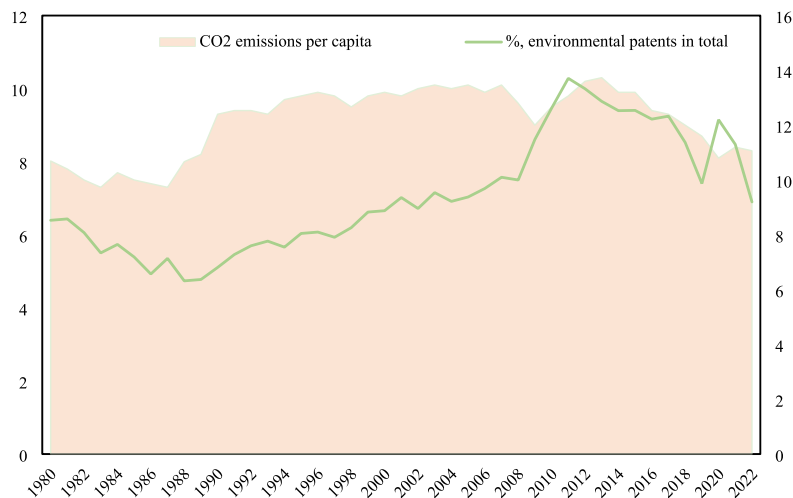
According to endogenous economic growth theory, the increase in R&D activities and technological innovation enhances factor productivity and output. However, the effect of technological innovation on environmental quality, particularly greenhouse gas emissions, remains uncertain (Chen and Lee 2020). Because technology triggers new products, which can negatively affect environmental sustainability by directly increasing energy consumption. On the other hand, technological progress can improve environmental pollution by contributing to energy efficiency. At this point, the role of technology subcomponents,

such as R&D and patents, becomes essential. Rennings (2000) divided the determinants of environmental innovation into three groups. These groups are the supporting effect of technology, the attractive effect of markets, and the determining effect of environmental regulations. These effects encourage companies to produce environmentally friendly products and consumers to consume them. In addition, legal regulations may force companies to produce environmentally friendly products, which could contribute to environmental sustainability. Green patents present an additional strategy opportunity for governments, particularly in reducing environmental pollution through energy efficiency (Serener et al. 2022; Kirikkaleli et al. 2023). Another essential advantage of clean technologies is that, unlike many other sectors, they support economic growth while reducing environmental pollution (Aggeri 1999). Therefore, the critical point is that these environmental patents and technological innovations may support the launch of new products, resulting in more energy consumption and environmental pollution (Cheng et al. 2019).

Japan has set ambitious targets within the framework of the Paris Agreement and is committed to achieving a net-zero emission target by 2050. In this context, using 2013 business-as-usual levels as a baseline, Japan plans to reduce emissions by 46% by 2030 (UNFCCC 2023). The Nationally Determined Contributions (NDCs) of Japan, which commit to a 46% reduction in emissions, clearly indicate that policymakers should focus on the industrial, commercial, residential, transportation, and energy conversion sectors to meet these targets. However, even if these targets are met, additional emissions gaps for achieving net-zero may emerge due to rising demands, economic activity, and the development of new products. In this scenario, environmental patents could provide additional policy tools for Japanese policymakers to address the emission gap necessary to meet net-zero targets.

In Figure 1, the left axis represents CO<sub>2</sub> emissions per capita, while the right axis illustrates the share of environmental technologies in total patents in Japan. Accordingly, CO<sub>2</sub> emissions per capita were 8 kton in 1980 but peaked at 10.2 kton in 2012 and 8.3 kton in 2022. The share of environmental patents in total patents was approximately 8.53% in 1980, reached its highest level in 2011 at nearly 14%, and then declined to 9.2% in 2022. As can be seen, both indicators showed an increasing tendency between 1980 and 2012, after which they showed a discernible declining trend. While the decrease in CO<sub>2</sub> emissions is a positive sign of environmental quality, the decline in the rate of environmental patents suggests that more aggressive efforts are required in environmental technology and innovation. When it comes to comparison with other developed nations, one can see that the share of patents on environmental technologies in all technologies is above the OECD average (8.1%). In addition, this rate is higher than many developed economies such as the United States (6.52%), Germany (6.08%), and France (4.84%), according to OECD (2024).

As part of the Paris Agreement, Japan declared a net-zero emission target by 2050. However, policymakers face some challenges. Since the Fukushima accident in 2011, nuclear energy has faced significant criticism in Japan. As a result, many nuclear reactors have been closed or had their capacity reduced.



**FIGURE 1** | Environmental patents and per capita CO<sub>2</sub> emissions (Japan, 1980–2021). Source: OECD 2024; World Bank 2024b.

However, ensuring Japan's long-term energy supply security without nuclear energy poses a substantial challenge. According to Statista (2024), the share of nuclear energy in total electricity production was 29% in 2010, prior to the Fukushima disaster. By 2014, this figure had dropped to almost 0%. Nevertheless, the percentage has gradually increased since then, reaching 5.6% in 2023. For this reason, policymakers are under pressure to achieve net-zero emissions, despite the challenges, because nuclear energy produces no emissions and helps mitigate emissions in the long run. Therefore, without nuclear power, Japan might not achieve the net-zero target by 2050. As an industrialized country, Japan has many advantages in achieving sustainable development due to its advanced financial system, infrastructure, technological capacity, and research activities. Japan is also an essential promoter of environmental innovation, research, and patents. The country also set ambitious targets under the Paris Agreement and submitted NDCs, which declare to reduce emissions by 46% by 2030 and reach the net-zero target in 2050. However, Japanese policymakers may need additional strategies to fill possible emission gaps in the future. In this direction, we hope environmental patents could play a vital role in mitigating emissions through energy efficiency and productivity. Therefore, this study examines whether Japanese environmental innovation policies help mitigate environmental degradation and realize the net-zero targets and SDGs. In addition, the study explores Japan's energy outlook and discusses the possible threats and opportunities in terms of the energy mix and the competition between coal and natural gas. To this end, the study applies novel and robust empirical methods like the Fourier ARDL cointegration approach. This method also considers smooth structural transitions. Therefore, we expect robust empirical results from the analysis.

The study is organized as follows: (i) The first section provides theoretical information on environmental sustainability and technological innovation, and discusses Japan's environmental patent view. (ii) The second section demonstrates the literature review. (iii) The third section explains the empirical methodology and data. Furthermore, it reports the test results and discusses the findings. (iv) The last section summarizes empirical results and presents specific policy recommendations to help Japanese policymakers achieve the SDGs and the net-zero target.

## 2 | Literature Summary

There are many empirical studies on sustainable development in the environmental economics literature. Since the main parameter of this paper is environmental patents, we decided to divide the literature into two parts. While the first section encompasses research on environmental patents, the second section elucidates environmental sustainability in Japan.

Studies examining the impact of green patents on environmental sustainability generally reach a positive finding. These studies use variables such as green patents, eco-innovation, environmental technologies, and green patenting. According to Popp (2005), to understand the relationship between environmental degradation and technology, it is necessary to focus on the interaction of environmental policy and patents. Kirikkaleli et al. (2023) examined the link between green patents and environmental sustainability in the United States for 1970–2018. They captured a positive link between green technologies and environmental quality. Therefore, the government should apply environmental policies. By considering patents, Hu et al. (2021) found a positive linkage between patents and environmental sustainability in ASEAN countries. Pata et al. (2024) examined the relationship between eco-innovation and environmental sustainability in Germany. They found that environmental patents might be an efficient tool to achieve the net-zero emission target by 2045. The reason behind this is that environmental patents might provide additional strategies for the possible emission gaps. Likewise, Aneja et al. (2024) confirmed that green innovation supports environmental sustainability in G-20 countries. Serener et al. (2022) focused on Sweden over the period 1995Q1–2019Q4 and found that green patents and renewable energy contribute to environmental sustainability, whether economic growth and financial development have a negative impact on it. The authors advise policymakers to apply strict regulatory policies regarding financial development and invest in environmental patents and renewable energy to increase environmental sustainability. Razzaq et al. (2023) also found that clean finance and renewable energy technologies stimulate green growth in China. A positive relationship between technological innovation and environmental sustainability is

captured for Pakistan (Chunling et al. 2021), Southeast Asian countries (Rout et al. 2022), BRICS economies (Ali et al. 2022; Rauf et al. 2023), China (Xu et al. 2023), South Asia (Wen et al. 2022), and G-10 countries (Guan et al. 2022). These studies generally suggest that policymakers increase incentives for environmental patents and ease investments in these sectors. However, Destek and Manga (2021) found no significant association between technological innovation and environmental sustainability in Big Emerging Market (BEM) nations. Sun et al. (2008) also claim that China's environmental technology innovation capacity was inefficient worldwide since the share of patents was low and the business sector did not pay attention to technological innovation.

Yabar et al. (2013) investigated the linkage between Japanese environmental policy and technological innovation. They determined that environmental regulations triggered technological advancements from 1990 to 2008. They suggest increasing incentives for technological innovations through effective regulations. Tatsuo et al. (2013) supported this finding. They examined the manufacturing sector in Japan over the period 1964–2008. They underlined product innovation and concluded that there is a strong relationship between innovation, regulation, standardization, and market structure. Fankhauser et al. (2013) also examined 110 manufacturing firms in eight countries (China, Germany, France, Italy, Japan, South Korea, the United Kingdom, and the United States). They found that Japan benefited the most from the green economy thanks to environmental competitiveness and innovation. Aldieri et al. (2019) examined 240 US, European, and Japanese firms. They claim that environmental technologies have positive impacts on the firms' performance. However, the dimension of this impact varies based on the country, and a green economy has some long-term limitations. Motohashi et al. (2025) also found that a rise in university patenting significantly influences later innovation, following the national university reform in 2004. Therefore, the study highlights the importance of institutional factors in patenting, such as universities. Fujii and Managi (2016) investigated the factors that led to environmental protection-connected technological advancements in Japan for the period 2001–2010. They found that the public and private sectors trigger green patent applications through efficiency. According to the paper, the private and governmental sectors have different factors that influence environmental patent applications. The primary reason for the rise of private enterprises is their percentage of environmental patent applications. In the meantime, the public sector enhanced the efficiency of R&D activities by increasing the number of patent applications. Singh et al. (2017) investigated the linkage between environmental policy and innovation by comparing Japan and European Union countries. They found that environmental regulation serves as a catalyst for innovation, and Japan implies more effective environmental strategies for promoting innovation than European Union countries. Kartal et al. (2023) focused on environmental sustainability through the load capacity factor from 1974 to 2018. Empirical results show that renewable energy R&D expenditures have a mitigating impact on environmental degradation. The study also reveals that nuclear energy research does not impact environmental sustainability. For this reason, the study suggests that Japanese policymakers should focus on renewable energy

research rather than nuclear energy. Ahmed et al. (2022) also support this finding for Japan from 1974 to 2017. However, they found that nuclear energy could be an effective tool to mitigate CO<sub>2</sub> emissions. Pei et al. (2023) investigated the impact of financial development and industrial structure on environmental quality. According to the results, these variables positively affected environmental quality in Japan over the period 1995–2020.

### 3 | Data and Model

Gallant and Souza (1991) asserted that the Fourier approach can identify sharp structural shifts, particularly in small samples. In this study, we utilized the Fourier ARDL approach developed by Yilanci et al. (2020). This method is notable for several advantages. First, in the ARDL approach, the explanatory variables may be stationary at level  $I(0)$  or first difference  $I(1)$ , as long as the dependent variable is  $I(1)$ . Thus, the requirement for the series to be stationary of the same order is more flexible. Furthermore, since the ARDL cointegration test relies on the error correction model, it provides consistent and robust statistical results. Finally, the Fourier ARDL test accommodates internal structural breaks and yields reliable outcomes in small samples (Yilanci and Pata 2020).

This paper investigates the relationship between CO<sub>2</sub> emissions, environmental patents, economic growth, and energy consumption in Japan from 1975 to 2021 by applying the Fourier ARDL approach. Equation (1) represents the model for the empirical analysis.

$$LCO_{2t} = \beta_1 EP_t + \beta_2 GDP_t + \beta_3 EN_{it} + \varepsilon_t \quad (1)$$

where CO<sub>2</sub>, EP, GDP, and EN stand for per capita CO<sub>2</sub> emissions, the share of patents on environmental technologies, GDP growth, and primary energy consumption growth, respectively. We chose the independent variable series as growth rates to examine the impact of growth trends on per capita CO<sub>2</sub> emissions. In this way, we could also forecast whether there is a decoupling between economic growth, energy consumption, and environmental degradation. We also employ novel and robust empirical methods, such as the Fourier ARDL cointegration test. The advantage of the Fourier ARDL approach is that it considers smooth structural shifts, such as the 2008 global crisis, COVID-19, and the Fukushima nuclear disaster. Table 1 shows data descriptions.

The ARDL method, developed by Pesaran et al. (2001), considers both the  $F$  and  $t$  statistics. These statistics inform readers about the validity of the hypothesis. The primary hypothesis is accepted if the  $F$ -test is lower than the critical upper bound values, indicating that there is no long-term cointegration linkage between the parameters. Equation (2) presents the ARDL model discussed in this paper:

$$\begin{aligned} \Delta CO_{2t} = & \beta_0 + \beta_1 CO_{2t-1} + \beta_2 GDP_{t-1} + \beta_3 EN_{t-1} \\ & + \beta_4 EP_{t-1} + \sum_{i=1}^{\rho-1} \phi_i' \Delta CO_{2t-i} + \sum_{i=1}^{\rho-1} \delta_i' \Delta GDP_{t-i} \\ & + \sum_{i=1}^{\rho-1} \theta_i' \Delta EN_{t-i} + \sum_{i=1}^{\rho-1} \vartheta_i' \Delta EP_{t-i} + et \end{aligned} \quad (2)$$

In Equation (2),  $\Delta$  and  $\rho$  represent the first difference operator and the lag length, respectively. As we mentioned above, Pesaran et al. (2001) formed the  $F$ -test ( $F_A$ ) and  $t$ -test ( $t$ ) to capture a cointegration association between the parameters.

$$H_{0A}: \beta_1 = \beta_2 = \beta_3 = 0 \quad (3)$$

$$H_{0B}: \beta_1 = 0 \quad (4)$$

McNown et al. (2018) presented a different  $F$ -test ( $F_B$ ). This test checks whether the primary hypothesis is validated.

$$H_{0C}: \beta_2 = \beta_3 = 0 \quad (5)$$

To accept the cointegration, on the condition that Equations (3–5) are rejected, we can approve the existence

of cointegration. One of the most essential advantages of the Fourier ARDL method is that it delivers more robust results as it considers the structural shifts. Another advantage is presenting empirical results without using dummies (Yilanci and Pata 2020).

$$d(t) = \sum_{k=1}^n ak \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n bk \cos\left(\frac{2\pi kt}{T}\right) \quad (6)$$

In Equation (6),  $n$  shows the number of frequencies,  $k$  is the number of specific frequencies,  $t$  is the trend, and  $T$  is the sample size. The frequency value for the model is reached from the studies of Ludlow and Enders (2000) and Becker et al. (2006). Equations (7) and (8) depict the Fourier functions and the Fourier model, respectively.

$$d(t) = \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (7)$$

$$\begin{aligned} \Delta CO_2t = & \beta_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 CO_2t - 1 \\ & + \beta_2 GDPt - 1 + \beta_3 EPt - 1 + \beta_4 ENt - 1 \\ & + \sum_{i=1}^{\rho-1} \varphi_i' \Delta CO_2t - i + \sum_{i=1}^{\rho-1} \delta_i' \Delta GDPt - i \\ & + \sum_{i=1}^{\rho-1} \theta_i' \Delta EPt - i + \sum_{i=1}^{\rho-1} \vartheta_i' \Delta ENt - i + et \end{aligned} \quad (8)$$

**TABLE 1** | Data definitions.

Data	Unit	Source
CO <sub>2</sub> emissions (CO <sub>2</sub> )	Per capita	Our World in Data (Ritchie et al. 2023)
Patents on environmental technologies (EP)	% in total patents	OECD (2024)
Primary energy consumption (EN)	% Growth	BP Statistical Review of World Energy (2024)
Economic growth (GDP)	% Growth	World Bank (2024a)

**TABLE 2** | Unit root test.

Variables	Fourier ADF test statistics	$F$ -test	ADF (level)	ADF ( $\Delta$ first difference)
CO <sub>2</sub>	-2.79	5.27	-1.52 (0.51)	-3.49* (0.01)
EP	-2.80	6.29	-0.83 (0.80)	-3.54* (0.01)
GDP	-4.03	4.19	-2.01 (0.28)	-5.69* (0.00)
EN	-4.50	12.93*	-1.31 (0.62)	-2.63*** (0.10)

Note: The Fourier ADF critical values are 10.35, 7.58, and 6.35 for 1%, 5%, and 10%, respectively.

**TABLE 3** | FARDL test results.

OF	$F_A$	Bootstrap critical values (BCV)			$t$	BCV			$F_B$	BCV		
		10%	5%	1%		10%	5%	1%		10%	5%	1%
4.40	9.58**	4.75	6.20	11.49	-6.08*	03.51	-3.97	05.02	4.61***	4.48	6.09	11.25

Note: OF illustrates optimal frequency. \*, \*\*, and \*\*\* indicate 1%, 5%, and 10% significance levels, respectively.

### 3.1 | Empirical Results

We employ the Fourier Augmented Dickey–Fuller (ADF) test for unit root checks. Based on the Fourier ADF unit root test outcomes, one can see that the Fourier trigonometric terms are insignificant except for EN. In this situation, Enders and Lee (2012) suggest employing the traditional ADF unit root approach. Table 2 reveals unit root test findings.

According to the ADF test results, all series are stationary at first difference while they are not stationary at their level values. After this step, we could seek a long-term cointegration relationship. Table 3 presents the Fourier ARDL cointegration test results.

There are three tests ( $F_A$ ,  $t$ , and  $F_B$ ) for testing the FARDL long-term cointegration relationship. All findings indicate a long-term cointegration at different significance levels. Since we captured a significant cointegration, we could determine the FARDL long-run model and get long-term coefficients. For this purpose, we apply the Fourier-based long-term estimation method. Table 4 depicts the FARDL model, and Table 5 presents Fourier-based long-term coefficients.

Fourier-based long-run estimation captured statistically significant findings for all independent variables. Findings reveal that

**TABLE 4** | FARDL model (1,1,1,1).

Conditional error correction regression				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.771486	0.864729	0.892171	0.3779
CO <sub>2</sub> (-1)*	-0.257826	0.090386	-2.852508	0.0070
GDP**	0.059801	0.028612	2.090059	0.0434
EP**	0.151365	0.050274	3.010786	0.0046
EN(-1)	0.053440	0.030746	1.738110	0.0903
D(EN)	0.033145	0.020809	1.592767	0.1195
@SIN(2*@ACOS(-1)*1*@TREND/47)	-0.002321	0.142594	-0.016278	0.9871
@COS(2*@ACOS(-1)*1*@TREND/47)	-0.422392	0.109282	-3.865145	0.0004

Note: \* and \*\* show the significance at 1% and 5%, respectively.

**TABLE 5** | Fourier-based long-term coefficients (FARDL model).

EP	GDP	EN
0.59*	0.23**	0.21**
(0.00)	(0.04)	(0.04)

Note: \* and \*\* show the significance at 1% and 5%, respectively.

energy consumption, economic growth, and environmental patents trigger CO<sub>2</sub> emissions in Japan from 1975 to 2021. We also employed the Fourier Toda-Yamamoto test to check whether we capture robust results.

In Table 6, we see a bi-directional causality relation between CO<sub>2</sub> and GDP. In addition, there is a unidirectional causality relation from EP and EN to CO<sub>2</sub>. According to the findings, one can confirm that the Fourier Toda-Yamamoto test results support the Fourier ARDL long-term coefficient test results in Table 5. These findings prove that empirical findings are robust and reliable.

Figure 2 shows the summary of the empirical findings. As shown, economic growth, energy consumption, and environmental patents fail to reduce CO<sub>2</sub> emissions in Japan.

#### 4 | Discussion

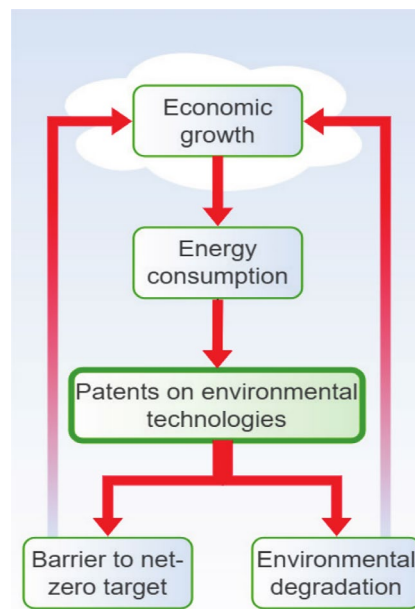
Based on the findings from the Fourier ARDL long-term coefficient test and Fourier Toda-Yamamoto test results, we add four essential comments and reasoning toward the empirical findings:

1. In Japan, GDP increases CO<sub>2</sub> emissions, which exacerbates environmental sustainability. This also complicates the decoupling between economic growth and CO<sub>2</sub> emissions. Therefore, it is clear that Japan has not yet started an effective transition to a clean economy. This finding is supported by studies showing that economic growth reduces environmental quality in Japan (Ahmed et al. 2022; Ikram et al. 2021; Shah et al. 2023).

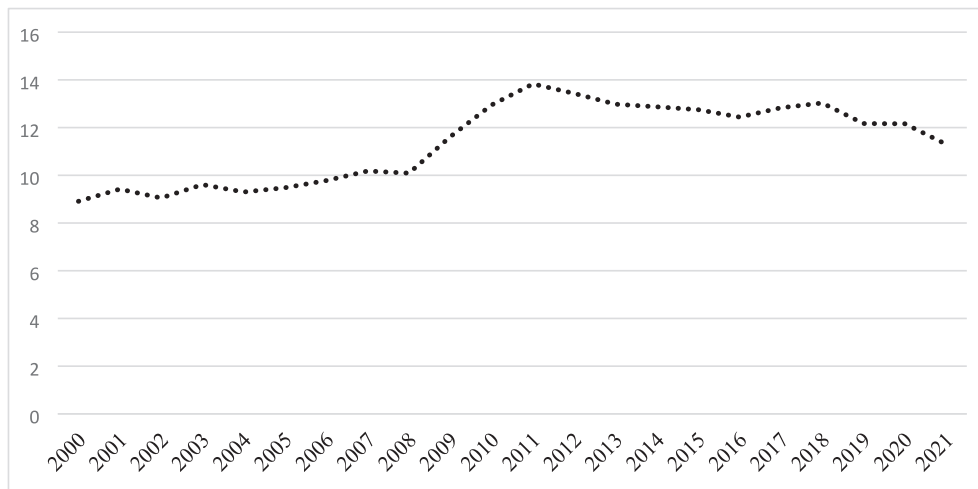
**TABLE 6** | Fourier Toda-Yamamoto causality test.

Variables	t-stat	p	t-stat	p	
CO <sub>2</sub> → GDP	13.79	0.03**	GDP → CO <sub>2</sub>	12.01	0.06***
CO <sub>2</sub> → EP	14.34	0.03**	EP → CO <sub>2</sub>	4.08	0.67
CO <sub>2</sub> → EN	11.77	0.07***	EN → CO <sub>2</sub>	4.17	0.65

Note: Numbers in parentheses represent the prob. values. \*\* and \*\*\* show the significance at 5% and 10%, respectively.

**FIGURE 2** | Summary of the findings.

2. As expected, energy consumption adversely affects environmental quality since fossil fuels predominantly meet Japan's energy demand. Due to the high level of fossil fuel consumption, energy usage represents the main barrier to achieving environmental sustainability. According to the Energy Institute (2024), the share of fossil fuels in primary energy consumption is 83.42% in 2023. However,



**FIGURE 3** | Share of environment technology patents in total technology patents. Source: OECD (2024).

it has been decreasing since 2012 from levels of 93.53%. These figures clearly reveal that Japanese policymakers should urgently focus on low-carbon energy resources and a green transition in the industry. A promising achievement is that the share of primary energy consumption from renewable sources has been increasing since 2000. While it was 4.82% in 2000, it reached 12.58% in 2023. This growth is essential to strengthen the progress of the green transition. This development has accelerated, especially in the post-Fukushima period, rising from 5.62% in 2012 to 12.58% in 2023. Additionally, we see that the role of nuclear power has weakened since the Fukushima disaster in 2011. The share of nuclear power in primary energy was 13.01% in 2010; however, it faced a significant decline in 2015, falling below 1%. In 2023, this ratio is 3.99%.

3. Our primary variable—environmental patents—has a negative impact on environmental sustainability. This finding implies that environmental patents have yet to exert a significant influence on mitigating CO<sub>2</sub> emissions. Moreover, patenting environmental technologies increases energy consumption, indicating that environmental patenting strategies are not truly environmentally friendly in Japan. Therefore, we suggest that Japanese policymakers include environmental patents in their long-term environmental policy agenda. In this way, policymakers could find additional tools to achieve net-zero emission targets by 2050. Aldieri et al. (2019) also did not find a significant impact of cycling patents and environmental innovations in Japan. They claim this might be due to different dimensions of firm specifications. Based on this lack of significance in innovation, Tatsuo et al. (2013) believe that policies considering the life cycle process would be more successful regarding environmental quality.
4. We clarified the adverse impact of environmental patents on environmental sustainability by exploring data from OECD (2024).

Figure 3 illustrates a rising trend in the share of environmental patents since 2000. The share ratio was 8.91% in 2000, grew to 13.43% in 2011, and was 11.30% in 2021.

## 5 | Conclusion and Policy Recommendations

The world economy has dealt with several economic issues since 2020, mainly due to COVID-19 and the lagging financial effects of the pandemic and the energy crisis. First of all, the expansionary monetary policies implemented to eliminate the negative impact of COVID-19 on the economy have resulted in an inflation dilemma. Many countries in the world economy have been struggling with inflation and face the risk of economic stagnation. In addition, the war between Russia and Ukraine further deepened inflation by pushing global energy prices up. Countries tend to ignore the environment while fighting inflation. For instance, Germany temporarily reopened coal power plants to solve energy inflation. As can be understood from this example, countries can ignore the environment when economic problems arise, even if they are developed countries. Therefore, long-term and effective practices are needed to combat environmental pollution. In addition, countries should prioritize creative processes and augment the proportion of expenditure on innovation within their GDPs (Erdoğan et al. 2022). Energy efficiency could be a key factor for the policy option. Improvements in energy efficiency have long-term effects on the environment. At this point, environmental patents play an important role since they could reduce the energy consumed per unit, primarily by providing energy efficiency.

This study examines the relationship between environmental sustainability and environmental patents in Japan from 1975 to 2021 and employs novel econometric approaches such as the Fourier unit root, the Fourier ARDL cointegration, and the Fourier-based long-term coefficient techniques. As a result of the empirical findings, we first capture a long-run cointegration association between environmental sustainability, environmental patents, economic growth, and energy consumption. The Fourier-based long-term coefficient results show that environmental patents, energy consumption, and economic growth trigger environmental pollution in Japan. The negative impact of environmental patents reveals that environmental patents do not help emission reduction and net-zero targets. On the contrary, these activities likely create additional energy demand and consumption, which in turn triggers emissions because Japan's energy mix is highly dependent on fossil fuels. Indeed, this finding has some signals for Japan's environmental policies.

Policymakers should focus on further policies on green patents to increase environmental sustainability, which could be an effective tool for achieving SDGs and net-zero targets. Growing economies have higher energy demands, which lead to higher emissions and more pollution in the environment. Therefore, the adverse effects of economic growth and energy consumption on environmental sustainability are parallel with the theoretical expectations. However, environmental patents are thought to contribute to environmental sustainability. This finding is a contradiction in the existing literature. Upon closer examination, we discovered that Japan does not adequately promote patents for environmental technologies.

According to the Energy Institute (2024), the shares of total energy consumption in 2023 are as follows: oil (38.24%), coal (26.07%), natural gas (19.12%), renewable resources (12.58%), and nuclear (3.99%). Given this energy mix, it is obvious that Japan needs to make more ambitious efforts to achieve its net-zero emission target by 2050, as fossil fuels meet approximately 83.43% of the energy demand. Having high fossil fuel dependency (83%) dilutes the impact of environmental patents. In addition, high coal consumption significantly undermines the net-zero target. Therefore, environmental patents may improve efficiency but fail to offset rising emissions from high-carbon-intense fossil fuels such as coal and oil. Japan is a steadily growing economy. This growth trend increases energy demand. The high dependence on fossil fuels complicates meeting the increasing energy demand with green and clean resources. Therefore, increasing the share of clean and green energy resources in total energy consumption becomes more challenging. This circumstance impedes the positive impact of environmental patents on environmental sustainability by rendering it slow and limited. The optimistic scenarios are: (i) Japan's primary energy consumption and per capita energy use have been decreasing since 2000; (ii) despite the increasing share of renewable energy sources, the contribution of fossil fuels in primary energy is diminishing; and (iii) this trend is also supported by data showing the share of primary energy from low-carbon sources (Energy Institute 2024). Therefore, Japan's energy outlook presents both threats and opportunities for achieving the 2050 net-zero emissions target. In the context of environmental patents, we believe Japan can mitigate the threats in its energy mix. Patent applications focusing on environmental technology can contribute to long-term emissions reductions, primarily through improved energy efficiency. According to the International Energy Agency (2023), Japan's energy intensity has decreased since 1973. This suggests that Japan could achieve greater success in sustainable development and its net-zero target. Furthermore, Japanese companies may increase investments in environmental technology if these technologies, patents, and R&D expenditures positively impact their profitability and competitive advantage. To facilitate this, policymakers should encourage firms to invest in environmental technologies.

After submitting NDCs, countries have sought solutions to achieve net-zero targets and ensure a sustainable planet for future generations. However, reality often exceeds projections, as many analyses indicate that the net-zero target significantly surpasses all realized NDC targets (Hans et al. 2022). Therefore, additional strategies are needed alongside the NDCs presented

by countries (Supriya et al. 2023). This study posits that Japan can promote environmental patents to bridge potential emissions gaps while striving to meet its net-zero target. Recently, a decline in the share of environmental patents relative to total patents has been observed in Japan. Thus, increasing the number of environmental patents through advancements in technology, efficiency, and R&D efforts will benefit the economy and enhance environmental quality. Environmental patents play a crucial role in achieving a net decoupling of economic growth from environmental pollution in the long term. Energy consumption, regarded as a hurdle to net decoupling in Japan, could facilitate the green transition. Moreover, innovative developments in environmental patents will foster renewable energy and assist Japan's shift from high coal consumption to natural gas, a comparatively cleaner fossil fuel. Japan's renewable energy policies might not suffice for the emission reductions necessary to meet the net-zero target. To address this, policymakers should consider substituting coal with natural gas in the existing energy mix. Following the Fukushima disaster in 2011, Japan has faced criticism regarding nuclear energy, which records zero emissions, and the installed capacity of nuclear power plants has been declining since. These challenges place additional pressure on Japanese policymakers to achieve the net-zero emission target. Therefore, research focusing on emission reduction without nuclear energy will also assist Japanese policymakers in easing environmental sustainability targets.

This study suggests some practices to increase patent activity. For example, life cycle standards should be mandatory for environmental technologies. Environmental patents should be encouraged through tax breaks and per-patent incentives. Policymakers should also align environmental patent practices with Japan's SDGs and net-zero emissions target.

The limitation of this study is the sample period. Due to the lack of data on patents on environmental technologies after 2021, the sample covers the period from 1975 to 2021. It would be better to find recent shifts or technological advancements after COVID-19. Toward this gap, researchers might employ different series such as provisional patent data, R&D expenditure trends, and environmental technologies.

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The author has nothing to report.

#### **Ethics Statement**

The author has nothing to report.

#### **Consent**

The author has nothing to report.

#### **Conflicts of Interest**

The author declares no conflicts of interest.

#### **Data Availability Statement**

Available upon request from the corresponding author.

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