




Article

# The Role of Technological Innovation in a Dynamic Model of the Environmental Supply Chain Curve: Evidence from a Panel of 102 Countries

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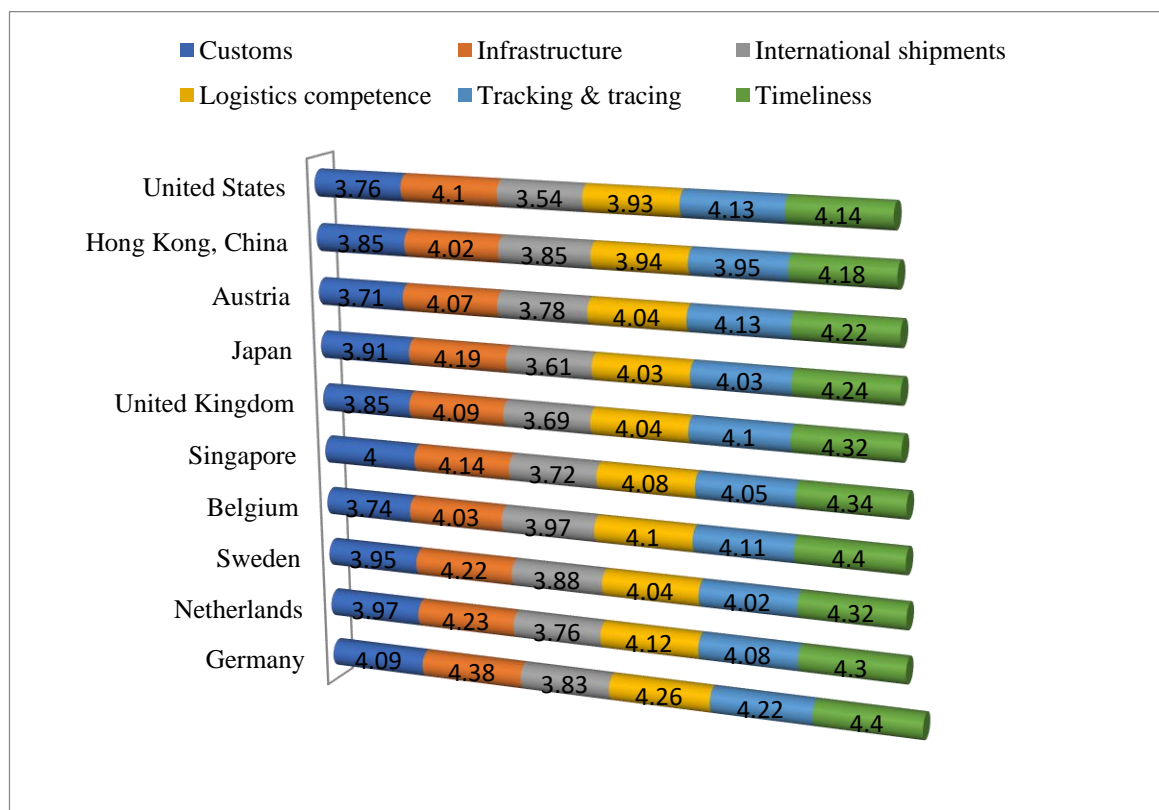


**Abstract:** Advancing smart production systems for green production remains a crucial priority for manufacturers, while the vision to achieve green supply chain management process (GSCMP) remains obstructed due to using less fuel-efficient technologies. This study suggested an intelligent logistics design that infused technological indicators with logistics performance indices (LPIs) to minimize carbon damages in a panel of 102 countries. The study used patent applications and trademark applications to analyze the technological progress, whereas LPIs—i.e., LPI-1 for assessing quality and competence services, and LPI-2 for trade and transport infrastructure—are used to determine supply chain management process across countries. The results show that carbon damages follow a U-shaped structure with technology-induced LPIs (TI-LPIs) and GDP per capita. The country's GDP per capita and TI-LPIs decrease carbon damages up to US\$15,000,000, while the moderation of patents application (and trademark applications) with LPI1 and LPI2 substantially decreases carbon damages up to US\$13,800,000 (US\$34,100,000) and US\$6,100,000 (US\$20,200,000), respectively. The causality estimates confirmed the growth-led carbon damages, technology-led carbon damages, growth-led logistics indices, and technology-led growth across countries. The results emphasized the need to move forward by adopting fuel-efficient technologies to minimize carbon damages across countries.

**Keywords:** green supply chain management; logistics performance indices; technological factors; carbon damages; economic growth; differenced panel GMM

## 1. Introduction

The United Nations proposed 17 developmental goals to the world community in 2015, among which climate change and smart technologies are mostly emphasized to minimize carbon damages and ensure sound and healthy economic recovery through which a country can reduce poverty and hunger issues [1]. The green supply chain management practices can mitigate climate issues through technological up-gradation in logistics activities and ensure low carbon base activities through which global average temperature could be reduced up to 1.5 °C, as suggested in COP25 in Madrid, 2019 [2–5]. According to the latest report of World Bank [6] that discussed the world ranking of overall logistics performance, Germany is placed in first position for logistics performance index (LPI) score, i.e., 4.19 out of 5, Netherlands in the second position, i.e., 4.07, Sweden, Belgium, Singapore, United Kingdom, Japan, Austria, Hong Kong China, and United States are placed in the following positions with an LPI range of 3.92 to 4.07. The LPIs consist of six critical dimensions: customs clearance process, quality of trade infrastructure, competitive price shipments, logistics competence and quality services, tracking and tracing consignments, and expected timeliness of delivery products. Figure 1 shows the top 10 logistics countries' profiles of their six key dimensions.



**Figure 1.** Top 10 Countries' Logistics Updates in 2018. Source: World Bank [6].

Technology-embodied economic growth is visible mainly in different industrial settings. The earlier literature favors technical up-gradation that supports countries' economic growth [7–11], while during large scale economies of production, the byproduct of carbon emissions is primarily discharged that sabotaged the United Nations sustainable development agenda [12–15]. Industrial sustainability could be achieved through sound environmental regulations and technology embodied the supply chain to provide a pathway to make sustainable development [16,17]. The smart technologies and production system could reduce the global environment; however, it is highly optimistic about improving logistics activities to become fuel-efficient, which largely supported corporate environmental and social responsibility [18–20]. Zaman and Shamsuddin [21] considered a panel of 27 EU countries by

using a time series data of 2007–2014 and found that LPIs have a healthy and positive relationship with energy efficiency that turned into increase countries economic growth. The critical dimensions of LPIs have a varied impact on the country's resource agenda. In general, the results show that due to high dependency on fossil fuel combustion, LPIs mainly deteriorate the natural environment in the form of high mass carbon emissions, which further interlink them with industrialization and financial liberalization policies, which negatively affect green supply chain management agenda across countries. Khan and Qianli [22] surveyed data of the United Kingdom from 1981 to 2016 to analyze the possible relationships among growth-related factors, LPIs, and environmental pollutants. The results show that renewable energy demand, FDI inflows, and economic growth are potential green supply chain management factors in a country. The policy mix related to the utilization of energy resources in the national portfolio is highly desirable to catch up on the green effects of LPIs in a country. Zaman [23] analyzed the role of renewable energy sources on the environmental cost of doing business in the context of BRICS countries using data from the period of 1995–2015. The results show that hydropower energy supported green supply chain management practices under the premises of economic growth and FDI inflows across countries. The study concludes that BRICS countries should require green energy policies to achieve energy efficiency that would play a vital role in attracting more foreign investors to produce environmental goods. Yu et al. [24] investigated the relationship between LPIs, energy demand, economic growth, and ecological indicators in a panel of 19 developed countries for a period 2008–2017. The results show that LPIs increase with energy demand, FDI inflows, and trade openness while they decrease along with an increase in carbon-GHG emissions across countries. The need for green logistics policies is highly desirable for generating corporate green payoffs. Aldakhil et al. [25] considered BRICS countries as a case study to propose an integrated supply chain management model, which is aggregated by various measures of LPIs, growth factors, and environmental resource indicators. Although in favor of logistics, the results drive economic growth; however, it further escalates carbon emissions, which is a severe concern for developing corporate environmental sustainable policies to mitigate environmental pollution through cleaner production technologies. Liu et al. [26] covered a larger panel of Asian countries for analyzing the possible linkages between ecological degradation and LPI by using data from the period of 2007–2016. The results show that some LPIs, industrialization, and urbanization escalate carbon emissions, while trade openness improves the natural environment through importing green products across countries. The study emphasized the need to improve the timeliness of logistics activities responsible primarily for increasing carbon emissions in the current scenario. Khan et al. [27] examined the potential determinants of green supply chain management across SAARC countries by utilizing a data period from 2001–2016. The results show that LPIs used a combination of fossil fuel combustions and non-renewable fuels that exert a negative impact on the country's economic growth and environment. Further, due to a lower quality of trade infrastructure, LPI increases carbon and fossil fuel combustion. In terms of the efficient customs clearance process, green supply chain management's vision is achieved mainly in the selected Asian countries. Table 1 shows the recent strikes of literature on technological innovation and environmental degradation across countries.

**Table 1.** Current Literature Review on Technology-Induced LPIs and Environmental Sustainability Agenda.

Authors	Time Period	Country	Technology Factors	Environmental Factors	Results
Liang et al. [28]	2006–2018	China	R&D expenditures	Environmental regulations, carbon emissions	ER↑TFP-LPI↑ R&D↑TFP-LPI↑
Lan et al. [29]	2006–2015	36 Chinese cities	Telecommunications	Sustainable megacities	INEFTEL↑INELPI↑ INEFTRD↑INELPI↑ TI↑CO <sub>2</sub> ↓ TOUR↑EG↑ TOUR↑CO <sub>2</sub> ↑
Kumail et al. [30]	1990–2017	Pakistan	Patents applications	CO <sub>2</sub> emissions	EG↑CO <sub>2</sub> ↑ EGΩCO <sub>2</sub>
Ahmad et al. [31]	1993–2014	24 OECD countries	R&D expenditures	CO <sub>2</sub> emissions	TI↑CO <sub>2</sub> ↑ EC↔EG TI↑EF↑
Ghazvini et al. [32]	1990–2016	G8 countries	Patents application	Renewable energy, oil, coal, CO <sub>2</sub> emissions	EF↑CO <sub>2</sub> ↓ TI↑CO <sub>2</sub> ↓ TI↑CO <sub>2</sub> ↓
Shahbaz et al. [33]	1984–2018	China	Patents applications	CO <sub>2</sub> emissions	EGΩCO <sub>2</sub> EXP↑CO <sub>2</sub> ↑ FDI↑CO <sub>2</sub> ↑ EGΩCO <sub>2</sub>
Usman et al. [34]	1971–2014	South Africa	Globalization index	Energy demand, CO <sub>2</sub> emissions	EC↑CO <sub>2</sub> ↑ GLOB→CO <sub>2</sub> GLOB→EC NR↑FD↓ TI↑FD↑ TOP↑FD↑ HK↑FD↑
Khan et al. [35]	1987–2017	China	Patents applications	Natural resources	EGΩCO <sub>2</sub>
Saleem et al. [36]	1980–2015	10 Asian countries	Patents applications	CO <sub>2</sub> emissions	EG↑EPI↑
Azimi et al. [37]	2006–2015	China	Environmental policy innovation	SO <sub>2</sub> , NO <sub>x</sub> emissions	EG↑CO <sub>2</sub> ↓ TI↑CO <sub>2</sub> ↓
Ibrahiem [38]	1971–2014	Egypt	Patents applications	CO <sub>2</sub> emissions	FD↑CO <sub>2</sub> ↑ EG↑CO <sub>2</sub> ↑

Note: ER shows environmental regulations, TFP-LPI shows total factor productivity of LPIs, INEFTEL shows inefficiency in telecommunication, INELPI shows inefficiency in LPI, INEFTRD shows inefficiency in trade infrastructure, TI shows technological innovations, EG shows economic growth, CO<sub>2</sub> shows carbon emissions, TOUR shows international tourism, EC shows energy consumption, EF shows energy efficiency, EXP shows exports, FDI shows foreign direct investment inflows, NR shows natural resources, FD shows financial development, TOP shows trade openness, HK shows human capital, NO<sub>x</sub> shows nitrogen dioxide, SO<sub>2</sub> shows sulfur dioxide, EPI shows environmental policy innovation, ↑ shows increases, ↓ shows decreases, → shows unidirectional causality, and Ω shows inverted U-shaped relationship.

### *Contribution of the Study, Research Questions and Objectives of the Study*

The study has a novel contribution in the present scholarly work from three different perspectives; firstly, the study used technology-induced logistics performance indices in carbon modeling, which is relatively less likely to be used in the existing studies [39,40]. Secondly, the study used the moderation effect of technological indicators, including patent application and trademark applications with logistics performance indices related to quality services and trade infrastructure to assess the non-linear relationship with carbon damages across countries. The previous studies are less likely to determine the moderation effect with the stated combination in carbon modeling in a diversified panel of countries. Finally, the study used few control variables, including GDP per capita, insurance and financial services, industry value-added, and medium & high tech industry in carbon modeling that is important to assess inverted U-shaped Environmental Kuznets Curve (EKC) hypothesis, industry associated emissions, green financing and insurance coverage, and high-tech pollution intensity level across countries. The earlier studies limited to cover these factors in different economic settings [41–45].

Based on the soundness of the study, the study proposed a set of research questions to assess the potential causal factors of carbon damages that increase the cost of carbon abatement across the globe, firstly, *do supply chain management practices inflame sustainable enterprise policies that negatively lead to the country's green developmental projects?* This question is essential in the two main perspectives; first, the manufacturing firms are mainly involved in delivering consignments to the outreach clients, using fossil fuel energy, vehicles, and managing trade infrastructure; thus, firms need strong logistics support to complete the stated tasks. Logistics activities require more power to gear their running operations; therefore, their activities cause severe environmental pollution that raises environmental degradation challenges across countries. Secondly, the negative environmental externalities of logistics activities deteriorate the national agenda of green development, which suffers due to increased healthcare expenditures because of rising pollution. In monetary aspects, manufacturing firms enjoy surplus profit at the cost of the country's vision of green and healthy development, which increases economic and financial distress across countries. The second research question is related to technological advancement in improving logistics performance that helps to minimize economic and financial sufferings. We investigate the reason behind high mass carbon emissions that lead to unsustainable supply chain management practices, i.e., *could advancement in technology-induced logistics performance improve supply chain management practices to enhance the quality of air indicators?* The question raised a severe reservation about the role of technology in advancement in green supply chain management practices on a global scale. Finally, the third question is directly linked to the country's economic growth, which assumes that country's growth-specific factors would mainly support technological advancement in a way to improve logistics performance indicators to limit carbon emissions. The question arises *whether continued economic growth, industry value-added, medium and high-tech industry, and insurance and financial services would support technology innovation to infuse logistics activities to reduce carbon abatement cost?* These three questions are mainly crucial in devising corporate-level policies and economic policies to better the country's vision to achieve green development.

Based on given research questions, the study made the following research objectives:

- (i) To examine the role of logistics performance indices in the cost of carbon emissions across countries.
- (ii) To investigate the dynamic linkages between technological factors and carbon damages in a panel of selected countries.
- (iii) To determine the potential impact of economic growth, industry value-added, medium and high-tech industry, and insurance and financial services on the cost of carbon emissions across countries, and
- (iv) To substantiate an inverted U-shaped relationship between carbon damages and economic growth, and carbon damages and technology-induced logistics performance indices across countries.

Using the dynamic panel econometric techniques, these objectives could be achieved to get robust inferences, including GMM estimator, VAR Granger causality, and innovation accounting matrix.

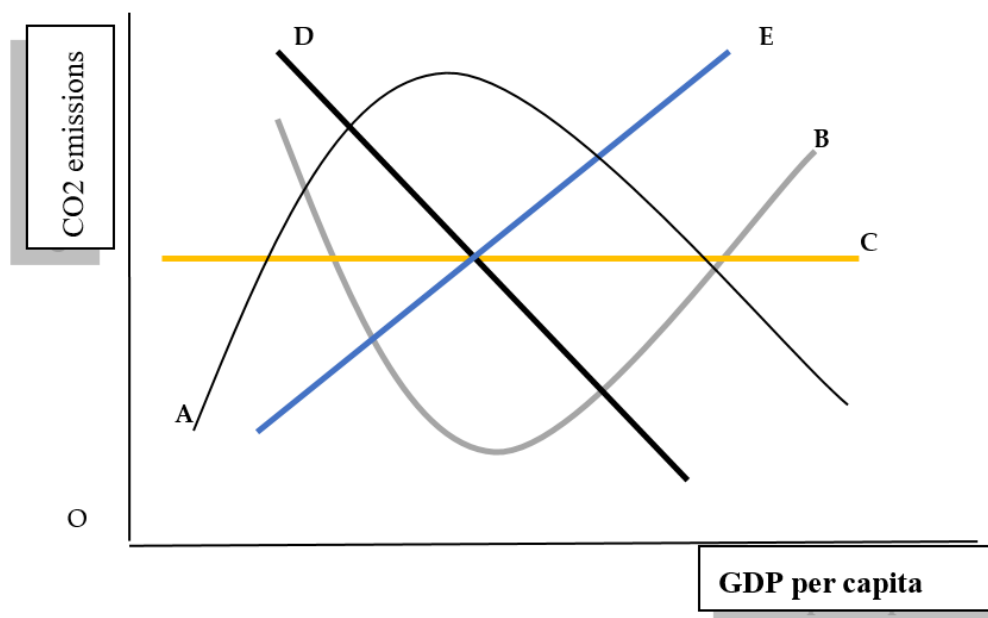
The given estimators would give sound reasoning about the given phenomenon's real situation and provide a list of policy implications to move forward for green supply chain practices at a global scale.

## 2. Materials and Methods

The data of the candidate variables reported in Table 2 is accessed through the World Bank [46] database, covering 102 countries from 2010 through 2018. The list of sample countries is shown in Table A1 in the Appendix A. The data of logistics performance indices is missing mainly during the period filled by preceding and succeeding values of the respective variables, where required. The same technique is used for other variables lost in some data points over time.

The study is evaluated three different alternative and plausible hypotheses:

- (i) Environmental Kuznets Curve (EKC): The EKC shows the non-linear relationship between income per capita and per capita carbon emissions at the second-degree quadratic version. The nominal GDP per capita and its second degree confined its positive and negative impact on carbon emissions, respectively, to substantiate an inverted U-shaped EKC hypothesis [47–49]. The other forms could also be found under different socio-economic and environmental factors across varied economic settings [50,51]. Figure 2 shows the five different possibilities of EKC hypotheses to clearly understand the given concept to use in a given study for more critical insights. Line A shows an inverted U-shaped relationship between the country's income and carbon emissions, which first increases then decreases carbon emissions due to vital environmental reforms being done through the country's economic growth. Line B shows the U-shaped relationship between the two stated factors that show carbon emissions decrease initially with the country's economic growth that later increases due to high industrialization caused by continued economic growth. Line C shows the flat EKC hypothesis, which argued that both the variables have no relationship. Line D shows monotonic decreasing function, while line E shows the monotonic increasing function that shows only one portion of the EKC hypothesis, either from the right side or left side, while the latter is insignificant.



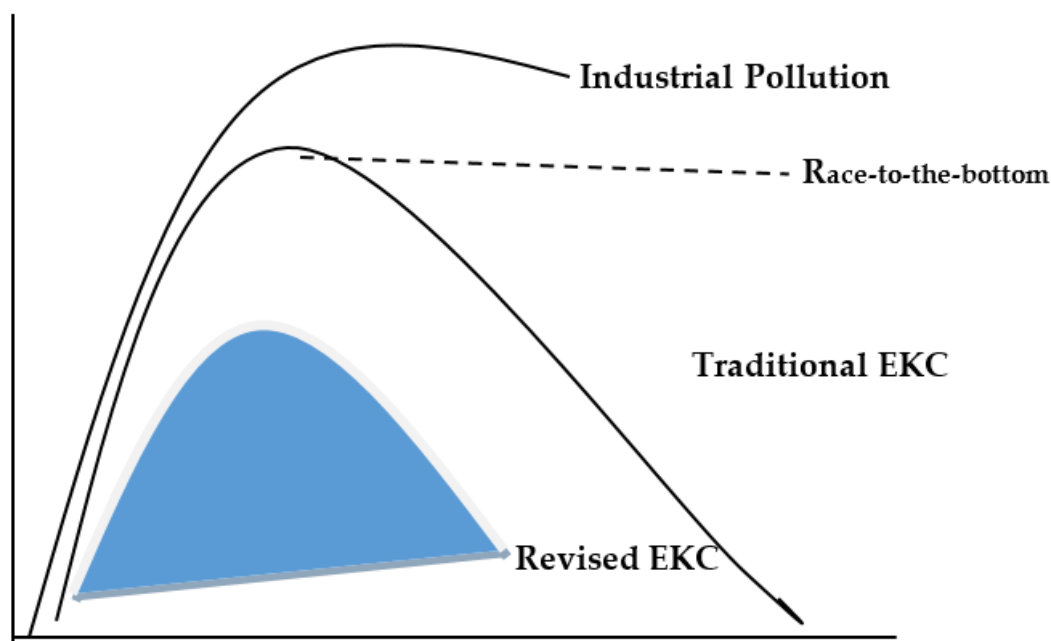
**Figure 2.** Different possibilities of EKC Formulation from Line A to E. Source: Extracted from the scholarly work of Dinda [50,51]. Note: 'A' line shows inverted U-shaped EKC hypothesis, 'B' line shows a U-shaped relationship, 'C' line shows the flat relationship, 'D' shows the monotonic decreasing relationship, and 'E' shows the monotonic increasing relationship between the variables.



**Table 2.** List of Variables. Source: World Bank [46].

Factors	Variables	Symbol	Measurement	Expected Sign	Hypothesis Testing
<b>Dependent Variable</b>					
Cost of Carbon Emissions	Carbon dioxide damages	CDAM	US\$	—	
<b>Independent Variables</b>					
Technology-Induced Logistics Performance Indicators (TI-LPI)	LPI: quality and competence	LPI1	Index value falls in between the lowest value 1 to highest value 5	+	Logistics-induced carbon damages
	LPI: trade and transport quality services	LPI2		+	
	Total patent applications	PATENTS	Total patent applications of residents and non-residents in numbers	+	Technology-induced carbon damages
	Total trademark applications	TMARK	Total in numbers	+	
	Moderation of LPI1 and PATENTS	$LPI1 \times PATENTS$	Moderation units	-	Inverted U-shaped relationship between carbon damages and TI-LPI
	Moderation of LPI2 and PATENTS	$LPI2 \times PATENTS$		-	
	Moderation of LPI1 and TMARK	$LPI1 \times TMARK$		-	
	Moderation of LPI2 and TMARK	$LPI2 \times TMARK$		-	
Technology Industry	Medium and high-tech Industry	MHTECH	% of manufacturing value added	+	Technology industry increases carbon damages
<b>Control Variables</b>					
Growth-Specific Factors	GDP per capita	GDPPC	Constant 2010 US\$	+	Inverted U-shaped relationship between CDAM and GDPPC to verify EKC hypothesis
	Square of GDP per capita	SQGDPPC		-	
	Industry value-added	IND	% of GDP	+	Industrialization increases the cost of carbon emissions
	Insurance and Financial Services	IFS	% of exports commercial services	+	Cost of carbon emissions increases due to an increase of insurance and financial services across countries.

- (ii) **Technology-Induced Emissions:** Grossman and Krueger [52] explored three different economic effects on the environment, i.e., scale effects, technological effects, and composition effects. The combination of these scales would help support the EKC hypothesis, i.e., the rapid economic transformation would increase the country's economies of scale that cause environmental degradation. Simultaneously, technological effects are most visible in developed countries that increase R & D expenditures to obsolete dirty polluting technologies and replace it with the cleaner technologies that ultimately affect the composition of production, which support the EKC hypothesis in a long-run. The less developed countries usually unscaled the dirty production due to easing environmental regulations, which ultimately increases carbon emissions.
- (iii) **New Toxic Pollutants, Race-to-the-Bottom Hypothesis, and Revised EKC Hypothesis:** The rapid industrialization shifts country's structural transmission mechanisms to using high-tech products that cause new toxic pollutants in the atmosphere, thus showing a single right-sided portion of EKC hypothesis. Further, due to developed countries' stringent environmental regulations to restrain the polluting industries, the production units shift widely from developed to developing countries, thus showing the race-to-the-bottom hypothesis. Finally, due to technology infusion and broadcasting, environmental awareness programs burden less developed countries to limit carbon emissions through fewer resources. Thus, the EKC hypothesis's kurtosis and its diameter fall short of the conventional EKC hypothesis (see Figure 3).



**Figure 3.** Different Scenarios of EKC Hypotheses. Source: Adapted from Taguchi [53].

- (iv) **Green Supply Chain Management Process (GSCMP):** The discussion of the EKC hypothesis is carried forward under logistics operations, which are embodied with technological progress to make an intelligent machine design fuel-efficient and advanced for smart and green production. It is expected that with the moderation of technical factors with logistics performance indices would make a green supply chain process that would be less sensitive to carbon emissions. Thus, it would form different possibilities of the EKC hypothesis across countries.

### 2.1. Theoretical and Econometric Framework

The study used an endogenous growth model to analyze the country's growth-specific factors in mitigating carbon emissions to substantiate the EKC hypothesis across countries. The endogenous growth model allows assessment of the importance of capital stock in economic production that



ultimately causes pollution that negatively impacts the global environment. While on the other side, the revenue generated from the economic output at the later stages could be spent on decreasing carbon abatement costs. The environmental quality thus can be improved by stringent environmental reforms and abatement policies. These are the basis of the EKC relationship between income and pollution across countries. The study gets benefited from the earlier studies of Dinda [50,51], Stern [47,54], and Shahbaz et al. [55,56], to make four simultaneous equations for assessing EKC hypothesis of carbon dioxide damages under technological –induced logistics performance indices (TI-LPIs), economic growth, industry value-added, and high-tech industry:

$$CDAM_{i,t} = \alpha_0 + \alpha_1 LPI1_{i,t} + \alpha_2 LPI2_{i,t} + \alpha_3 MHTECH_{i,t} + \alpha_4 PATENTS_{i,t} + \alpha_5 TMARK_{i,t} + \alpha_6 IFS_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$\therefore \frac{\partial CDAM_{i,t}}{\partial LPI1_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial LPI2_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial MHTECH_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial PATENTS_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial TMARK_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial IFS_{i,t}} > 0$$

$$CDAM_{i,t} = \alpha_0 + \alpha_1 LPI1_{i,t} + \alpha_2 LPI2_{i,t} + \alpha_3 GDPPC_{i,t} + \alpha_4 SQGDPPC_{i,t} + \alpha_5 PATENTS_{i,t} + \alpha_6 TMARK_{i,t} + \alpha_7 IND_{i,t} + \varepsilon_{i,t}$$

$$\therefore \frac{\partial CDAM_{i,t}}{\partial LPI1_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial LPI2_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial GDPPC_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial SQGDPPC_{i,t}} < 0, \frac{\partial CDAM_{i,t}}{\partial PATENTS_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial TMARK_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial IND_{i,t}} > 0$$

$$Turning.Point = \frac{-\alpha_3}{2\alpha_4}$$

$$CDAM_{i,t} = \alpha_0 + \alpha_1 LPI1_{i,t} + \alpha_2 PATENTS_{i,t} + \alpha_3 TMARK_{i,t} + \alpha_4 (LPI \times PATENTS)_{i,t} + \alpha_5 (LPI1 \times TMARK)_{i,t} + \alpha_6 IFS_{i,t} + \varepsilon_{i,t}$$

$$\therefore \frac{\partial CDAM_{i,t}}{\partial LPI1_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial PATENTS_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial TMARK_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial (LPI1 \times PATENTS)_{i,t}} < 0, \frac{\partial CDAM_{i,t}}{\partial (LPI1 \times TMARK)_{i,t}} < 0, \frac{\partial CDAM_{i,t}}{\partial IFS_{i,t}} > 0 \quad (3)$$

$$Moderation Turning Point = \frac{-\alpha_1}{\alpha_4} (for.PATENTS), \frac{-\alpha_1}{\alpha_5} (for.TMARK)$$

AugmentedModerationPoint

$$= \left[ \left( \frac{-\alpha_1}{\alpha_4} \right) \div \left( \sum \frac{LPI1_{i,t}}{N} \right) \right] (for.PATENTS),$$

$$\frac{-\alpha_1}{\alpha_5} \div \left( \sum \frac{LPI1_{i,t}}{N} \right) (for.TMARK) \quad (4a)$$

$$CDAM_{i,t} = \alpha_0 + \alpha_1 LPI2_{i,t} + \alpha_2 PATENTS_{i,t} + \alpha_3 TMARK_{i,t} + \alpha_4 (LPI2 \times PATENTS)_{i,t} + \alpha_5 (LPI2 \times TMARK)_{i,t} + \alpha_6 MHTECH_{i,t} + \varepsilon_{i,t}$$

$$\therefore \frac{\partial CDAM_{i,t}}{\partial LPI2_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial PATENTS_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial TMARK_{i,t}} > 0, \frac{\partial CDAM_{i,t}}{\partial (LPI2 \times PATENTS)_{i,t}} < 0, \frac{\partial CDAM_{i,t}}{\partial (LPI2 \times TMARK)_{i,t}} < 0, \frac{\partial CDAM_{i,t}}{\partial MHTECH_{i,t}} > 0$$

where,

$$Moderation Turning Point = \frac{-\alpha_1}{\alpha_4} (for.PATENTS), \frac{-\alpha_1}{\alpha_5} (for.TMARK)$$

AugmentedModerationPoint

$$= \left[ \left( \frac{-\alpha_1}{\alpha_4} \right) \div \left( \sum \frac{LPI2_{i,t}}{N} \right) \right] (for.PATENTS),$$

$$\frac{-\alpha_1}{\alpha_5} \div \left( \sum \frac{LPI2_{i,t}}{N} \right) (for.TMARK)$$

where, CDAM shows carbon emissions damage, LPI1 shows logistics quality services, LPI2 shows logistics quality in terms of transportation infrastructure and trade, GDPPC shows GDP per capita, IFS shows insurance and financial services, IND show industry value added, MHTECH shows medium and high-tech industry, PATENTS shows total patent applications, and TMARK shows total trade mark applications.

Equations (1)–(4a) shows that cost of carbon emissions is expected to be influenced by the greater use of logistics services, obsolete technologies, less insurance and financial coverage, industrialization, high-tech industry, and continued economic growth. These factors would further be analyzed under the EKC hypothesis domain through moderation of technology-induced LPIs to support the green supply chain management process (GSCMP).

The calculation of the turning point for the viability of EKC hypothesis remains a debatable issue, as Huang et al. [57], Lind and Mehlum [58], and many others emphasized the need to check the EKC hypothesis with some interval values, i.e., low and high interval values; hence EKC should fall between the two intervals. The study used different techniques to assess the viability of the EKC hypothesis under variables data and used ‘minimum value’ as the ‘lower interval value’ and ‘maximum value’ as the ‘higher interval’ value of the respective variables. The reason to use the range of the given variables

is to check whether the inverted U-shaped EKC hypothesis falls between the given variables or not? It would give more analytical wisdom and be a more pragmatic approach to remain in the data points and check the existence of the EKC hypothesis across countries. Further, the study used a moderation effect between technological factors and LPIs with the relation of carbon damages and checked the 'moderation turning point' with some desirable additions. The formula to find the turning point is mentioned in Equations (3) and (4a), which is further discussed below:

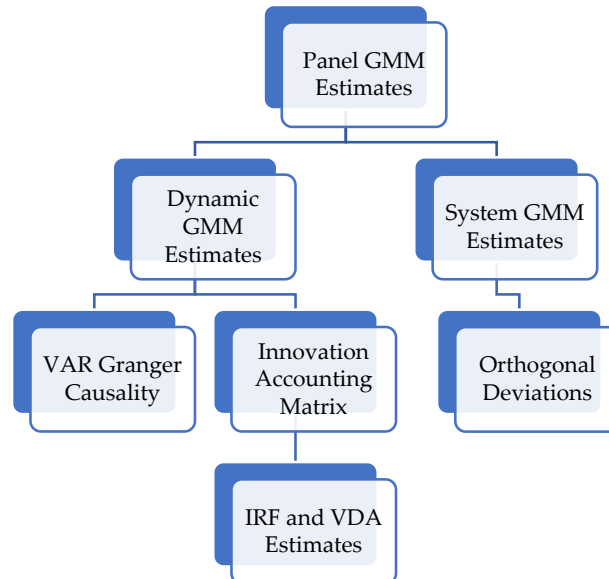
$$\begin{aligned} \text{Moderation Turning Point} &= \frac{-\alpha_1}{\alpha_4} (\text{for.PATENTS}), \frac{-\alpha_1}{\alpha_5} (\text{for.TMARK}) \\ \text{Augmented Moderation Point} &= \left[ \left( \frac{-\alpha_1}{\alpha_4} \right) \div \left( \sum \frac{LPIs_{it}}{N} \right) \right] (\text{for.PATENTS}), \\ & \frac{-\alpha_1}{\alpha_5} \div \left( \sum \frac{LPIs_{it}}{N} \right) (\text{for.TMARK}) \end{aligned} \quad (4b)$$

$$\begin{aligned} \text{Cost of Carbon Emissions} &= \text{Maximum value of CDAM} \div \text{Moderation Turning Point} \\ \text{Prevention of Losses/Gains from CDAM} &= \text{Cost of Carbon Emissions in US\$} - \\ & \text{Minimum Value of CDAM in US\$} \end{aligned} \quad (4c)$$

The given formula would help get information about the existence of EKC, estimation for calculation of the cost of carbon emissions that increase due to technology-induced LPIs, and losses/gains from CDAM across countries.

## 2.2. Research Methods

For obtaining the parameter estimates, the study utilized dynamic panel differenced GMM estimator in a group of 102 countries from 2010 through 2018. Figure 4 shows the research methods of the study.



**Figure 4.** Research Framework. Source: Author's extraction.

The key benefits of using this estimator are as follows:

- (i) It works under large cross-sections and limited time. In this study, there are 102 countries in a panel setting with a period of the last nine years.
- (ii) It handles more than one endogenous issue in the given models. The current study used simultaneous equations modeling; thus the chances of any known endogenous issue may mislead the model. Therefore, for the results' soundness, the differenced GMM estimator is good enough to observe this issue by including lagged instrumental variables.

- (iii) The problem of autocorrelation in panel settings might get affected by the studied parameter estimates. Thus, AR(1) and AR(2) would perform diagnostic tests to check any possible autocorrelation issues. If AR(1) does not fall in the 5% confidence interval, while AR(2) appears at a 5% significance level, the problem of autocorrelation problem would be resolved.
- (iv) The differenced GMM estimator is based upon the two-step procedure. In the first step, the regression is performed at differenced level, while in the second step, the lagged dependent variable included as a regressor in the given equations to remove simultaneity issues, and
- (v) The J-statistic and instrumental rank would be assessed to check the reliability of using given instruments as a true estimator in the given equations.

Bulajic et al. [59] and Borowski [60] rightly defining the research hypotheses in different economic settings. The study benefited from this and from using VAR Granger causality to check the following possible assumptions:

- Whether LPIs (and technological factors, and growth-specific factors) Granger cause carbon damages, and simultaneously whether carbon damages Granger cause LPIs (and technical factors, and growth-specific factors)? If both conditions hold, then the given relationship would be bidirectional in nature.
- Whether LPIs (and technological factors, and growth-specific factors) Granger cause carbon damages? The reverse does not hold the causal relationship, thus the given link would be unidirectional in nature.
- Whether carbon damages Granger cause LPIs (and technological factors and growth-specific factors)? If the reverse does not hold the same then the given relationship would be one-directional in nature.
- Whether LPIs (and technological factors, and growth-specific factors) do not Granger cause carbon damages, and simultaneously whether carbon damages do not Granger cause LPIs (and technical factors, and growth-specific factors)? In this case there will be no causal relationship between the stated variables.

Finally, the study used impulse response function (IRF) and variance decomposition analysis (VDA) to perform the following tasks:

- (i) To evaluate the relationship between the stated variables in inter-temporal settings.
- (ii) To assess the magnitude and direction between the variables over a time horizon.
- (iii) To check one standard error shock on the exogenous variables over the endogenous variable.
- (iv) These techniques would be desirable to get robust parameter estimates, which would further help devise policy implications.

### 3. Results

Table 3 shows the descriptive statistics of the variables. The cost of carbon emissions reaches its maximum value of 385,000,000,000, while at the same time LPIs shows good quality services both in terms of improving trade infrastructure and transportation facilities with an index value of 4.32 (LPI1) and 4.43 (LPI2) respectively. The country's GDP per capita, on average, shows US\$16,522.31 with a maximum value of US\$92,077.57 and a minimum value of US\$341.55. The average value of IFS, IND, and MHTECH is about 5.485% of commercial services exports, 27.520% of GDP, and 27.520% of manufacturing value-added. The patent applications included resident and non-resident applications, which were combined to obtain data of total patent applications across countries. Trademark applications are also used with the patent application data set to capture the technological evidence in a panel of selected countries. The minimum values of patent applications and trademark applications are 3 and 517, the maximum values are 1,542,002 and 2104411, and the average values are 24,479.16 and 45,722.60, respectively.

**Table 3.** Descriptive Statistics.

Methods	CDAM	LPI1	LPI2	GDPPC	IFS	IND	MHTECH	PATENTS	TMARK
Mean	9,110,000,000	2.974	2.918	16,522.310	5.485	27.610	27.520	24,479.160	45,722.60
Median	1,240,000,000	2.870	2.790	8,670.530	2.838	25.895	25.047	576	8976
Maximum	385,000,000,000	4.320	4.439	92,077.570	53.734	73.469	85.643	1,542,002	2,104,411
Minimum	14,143,239	1.681	1.471	341.554	0.00053	6.459	0.259	3	517
Std. Dev.	34,800,000,000	0.582	0.658	18,652.060	7.523	10.434	17.158	121,344.50	188,460.2
Skewness	7.523	0.387	0.475	1.620	3.063	1.502	0.558	7.911	9.347
Kurtosis	66.564	2.284	2.282	5.204	14.749	6.488	2.864	76.804	96.178

Note: CDAM shows carbon emissions damage, LPI1 shows logistics quality services, LPI2 shows logistics quality in terms of transportation infrastructure and trade, GDPPC shows GDP per capita, IFS shows insurance and financial services, IND show industry value added, MHTECH shows medium and high-tech industry, PATENTS shows total patent applications, and TMARK shows total trade mark applications.

Table 4 shows the correlation matrix and found that logistics indices (i.e., LPI1 and LPI2), GDP per capita, industry value-added, medium and high-tech manufacturing, and technological factors (i.e., PATENTS and TMARK) have a positive correlation with carbon damages with a correlation coefficient values of 0.226 (99% CI), 0.245 (99% CI), 0.057 (90% CI), 0.112 (99% CI), 0.206 (99% CI), 0.941 (99% CI), and 0.948 (99% CI), respectively. The result implies that logistics performance indices, technological factors, and growth-specific factors are the potential contributors to increasing carbon damages across countries. The logistics performance indices are positively influenced by the country's economic growth, insurance and financial services, medium and high-tech industry, and technological factors. The country's economic growth increases along with an increase in insurance and financial services, technical factors, and medium and high-tech industry. Insurance and financial services improved by technical factors, whereas an increase in medium and high-tech industry depends on technological advancement across countries. The correlation results confined their findings in three main aspects:

- (i) Logistics activities, technical factors, and growth-specific factors are considered the chief source to increase carbon damages across countries.
- (ii) The performance of logistics activities depends upon the country's financial ability and technological capabilities.
- (iii) Country's economic growth depends upon advancement in the technical factors and insurance and financial services in a panel of selected countries.

**Table 4.** Correlation Matrix.

Variables	CDAM	LPI1	LPI2	GDPPC	IFS	IND	MHTECH	PATENTS	TMARK
CDAM	1								
LPI1	0.226 (0.000)	1							
LPI2	0.245 (0.000)	0.950 (0.000)	1						
GDPPC	0.057 (0.083)	0.765 (0.000)	0.801 (0.000)	1					
IFS	0.043 (0.192)	0.340 (0.000)	0.353 (0.000)	0.384 (0.000)	1				
IND	0.112 (0.000)	-0.126 (0.000)	-0.084 (0.010)	-0.025 (0.442)	-0.1134 (0.000)	1			
MHTECH	0.206 (0.000)	0.725 (0.000)	0.735 (0.000)	0.640 (0.000)	0.212 (0.000)	0.101 (0.002)	1		
PATENTS	0.941 (0.000)	0.249 (0.000)	0.276 (0.000)	0.113 (0.000)	0.051 (0.118)	0.077 (0.018)	0.224 (0.000)	1	
TMARK	0.948 (0.000)	0.197 (0.000)	0.215 (0.000)	0.013 (0.680)	0.013 (0.683)	0.121 (0.000)	0.182 (0.000)	0.899 (0.000)	1

Note: Small bracket shows probability value. CDAM shows carbon emissions damage, LPI1 shows logistics quality services, LPI2 shows logistics quality in terms of transportation infrastructure and trade, GDPPC shows GDP per capita, IFS shows insurance and financial services, IND show industry value-added, MHTECH shows medium and high-tech industry, PATENTS shows total patent applications, and TMARK shows total trademark applications.

The overall assessment of the correlation matrix gives new insights into the possible relationship between the stated variables. Thus there is a high need to analyze the functional relationship between the explained and explanatory variables to devise the green supply chain management process.

Table 5 shows the dynamic panel GMM estimates and found that logistics performance indices positively correlate with carbon emissions damages in Equations (1) and (2) estimates, which tend to increase carbon damages due to higher logistics activities across countries. The earlier studies largely supported this argument from different perspectives, i.e., Khan et al. [27] concluded that logistics activities have a detrimental effect on air quality in the form of massive carbon emissions released due to lacking fuel-efficient technologies used in the logistics operation. The study emphasized the need to use renewable fuels to perform logistics operations to achieve green supply chain agendas across countries. Kannan et al. [61] argued that environmental consideration in the logistics business is mainly inflamed with negative environmental externalities, among which carbon emissions are the primary factor linked with logistics operations. The need to redesign the reverse logistics network is imperative to minimize ecological concerns during global transportation decisions. Herold and Lee [62] discussed the importance of green logistics in carbon management practices. They argued that the logistics and transportation sectors keenly observed and implemented low carbon emissions policies; however, carbon reporting in inventory management largely ignored the opportunity to work for the green supply chain management process. Yang et al. [63] assessed city level logistics performance of carbon emissions. They found that the return is varied at the city level, as some cities are embodied with technological frontiers that are helpful to decrease substantial carbon emissions, thus the advancement in cleaner production and shipment is desirable to reduce negative environmental externalities across countries.

**Table 5.** Dynamic Panel GMM Estimates.

Variables	Equation (1)	Equation (2)	Equation (3)	Equation (4a)
CDAM <sub>t-1</sub>	0.750 (0.000)	0.690 (0.000)	0.735 (0.000)	0.759 (0.000)
LPI1	10,900,000,000 (0.000)	2,400,000,000 (0.002)	-2,200,000,000 (0.000)	—
LPI1 × PATENTS	—	—	26,791.25 (0.000)	—
LPI1 × TMARK	—	—	65,671.51 (0.000)	—
LPI2	259,000,000 (0.743)	4,610,000,000 (0.000)	—	-3,920,000,000 (0.000)
LPI2 × PATENTS	—	—	—	21,306.03 (0.000)
LPI2 × TMARK	—	—	—	70,507.03 (0.000)
MHTECH	712,000,000 (0.000)	—	—	1,220,000,000 (0.000)
PATENTS	25,224.44 (0.000)	38,866.71 (0.000)	-109,940.9 (0.000)	-82,279.44 (0.000)
TMARK	2,848.929 (0.003)	-3,495.45 (0.000)	-197,544.4 (0.000)	-25,5923.5 (0.000)
IFS	-249,000,000 (0.000)	—	-11,923,931 (0.000)	—
GDPPC	—	-825,980.9 (0.000)	—	—
SQGDPPC	—	16.072 (0.000)	—	—
IND	—	-302,000,000 (0.000)	—	—

Table 5. Cont.

Variables	Equation (1)	Equation (2)	Equation (3)	Equation (4a)
<b>Diagnostic Tests</b>				
J-statistic	27.191	38.768	35.963	32.298
Prob. (J-statistic)	0.453	0.066	0.092	0.221
Instrumental rank	34	35	33	34
<b>Arellano-Bond Serial Correlation Test</b>				
AR(1)	-1.671 (0.094)	-0.938 (0.347)	-1.088 (0.276)	-1.311 (0.189)
AR(2)	-3.488 (0.000)	-2.595 (0.009)	0.913 (0.361)	0.423 (0.672)

Note: Small bracket shows probability value. CDAM shows carbon emissions damage, LPI1 shows logistics quality services, LPI2 shows logistics quality in terms of transportation infrastructure and trade, GDP per capita, IFS shows insurance and financial services, IND show industry value-added, MHTECH shows medium and high-tech industry, PATENTS shows total patent applications, and TMARK shows total trademark applications.

The results further show that medium and high-tech industry and technological factors are affiliated mainly with increased carbon damage in the form of high carbon abatement cost. Simultaneously, adequate insurance coverage and green financing services reduce the intensity of carbon emissions damage across countries. The results, although not supported by the inverted U-shaped EKC hypothesis in the relation of the country's economic growth and carbon damages, however, tend to show a U-shaped relationship between them. The result implies that at the initial level, when the country's income is just at US\$341.54, the intensity of carbon damages was at a maximum of US\$385,000,000,000, however, after reaching US\$25,696.30, the cost of carbon emissions decreases at US\$1,50,00,000. However, at later stages, when the country's income grew more and reached its highest level, i.e., US\$92,077.57, the cost of carbon emissions reached again at its maximum level. The complete description can be found in Figure 5.

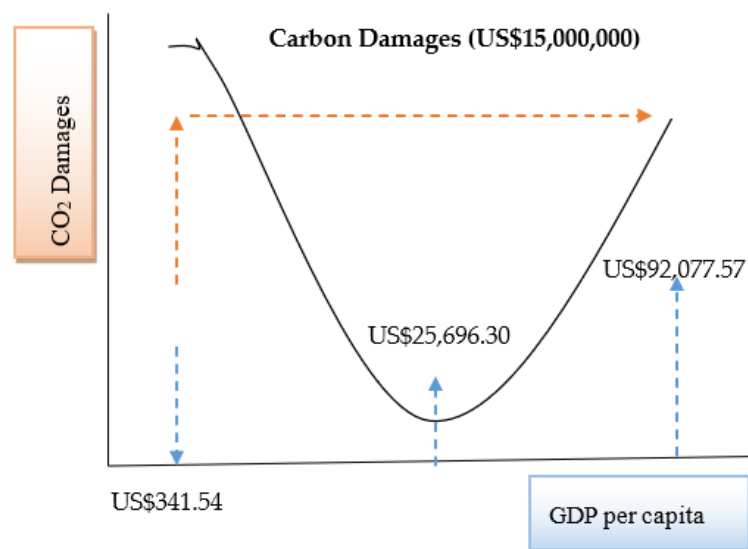
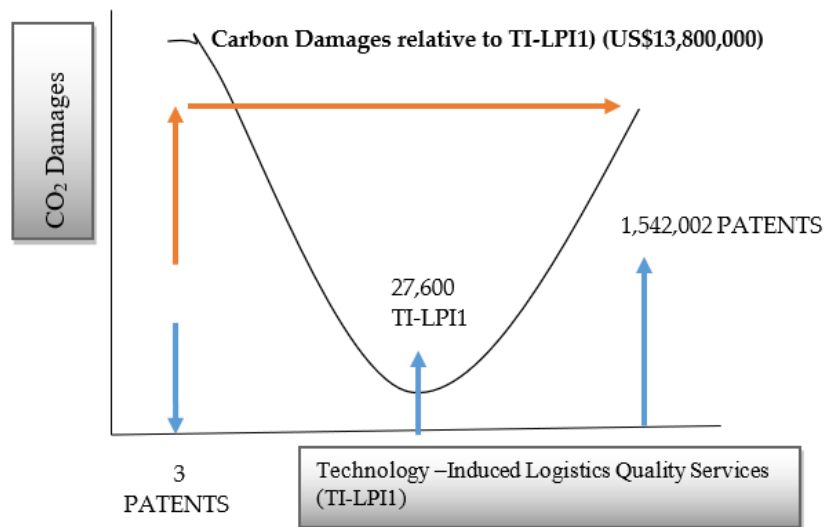


Figure 5. U-shaped Curve between Carbon Damages and Economic Growth.

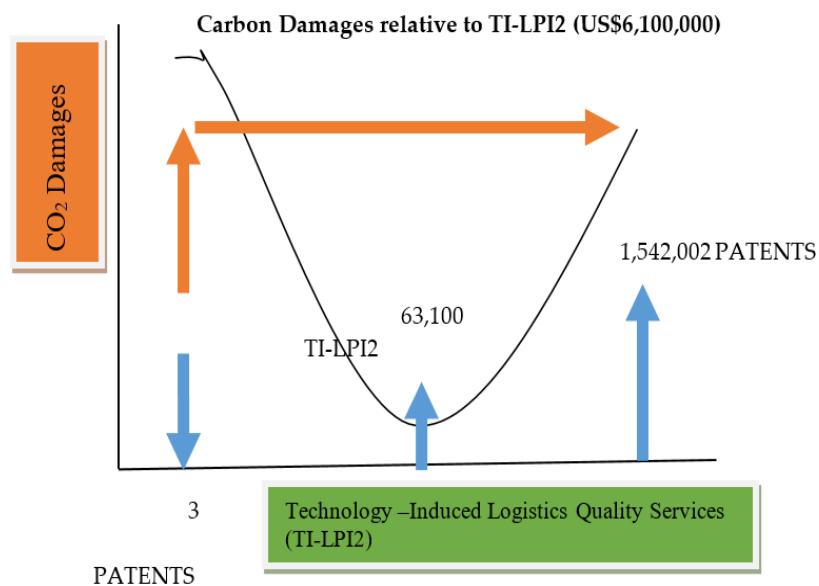
The moderation effect is included in Equations (3) and (4a). The technological factors, including patents application and trademark applications, are induced with logistics indices to assess green supply chain management practices and found a U-shaped relationship between carbon damages and moderation of technological factors. The result implies that carbon damages peak at US\$385,000,000,000 while patent applications are lowest at 3 in number; however, when technology-induced LPI1 was included in carbon modeling, the technology-induced LPI1 reaching 27,600 applications, it turns to decrease carbon damages up to US\$13,800,000. Further, when patent application reached its maximum level, i.e., 1,542,002 in number, carbon damages reached its maximum. Similarly, when the moderation



effect of patents application induced with LPI2, it mainly decreases carbon damages up to US\$6,100,000 at a threshold level of 63,100 patent applications. The complete description can be seen in Figures 6 and 7.

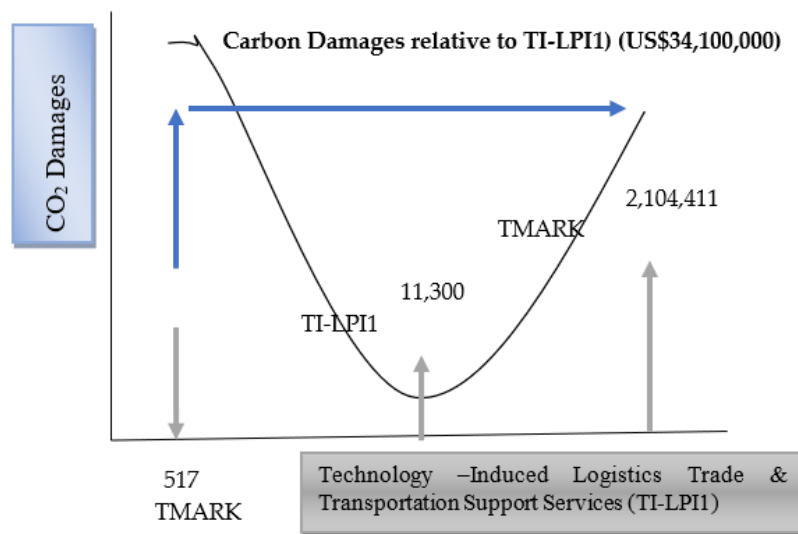


**Figure 6.** Moderation U-shaped Curve between Carbon Damages and Technology Induced Logistics Performance Indices (LPI1 × PATENTS).

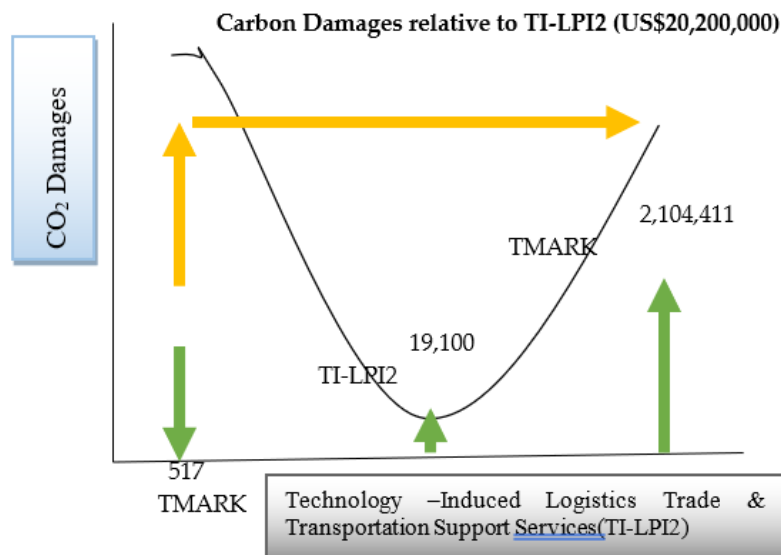


**Figure 7.** Moderation U-shaped Curve between Carbon Damages and Technology Induced Logistics Performance Indices (LPI2 × PATENTS).

Finally, the trademark applications are induced with LPIs and found that carbon damages first decrease along with an increase in technology-induced LPIs; however, at later stages, it escalates carbon damages beyond the threshold level. The given U-shaped relationship with trademark applications-LPI1 and carbon damages show that cost of carbon emissions increases at the lowest trademark applications of 517 in numbers while reaching threshold point, i.e., 11,300 applications, carbon damages decrease up to US\$34,100,000 for LPI1 and US\$20,200,000 for LPI2. Although there is a decline in carbon damages by adopting patent applications and trademark applications, however, the share of decreasing carbon damages is larger in trademark applications than patent applications. The complete description can be seen in Figures 8 and 9.



**Figure 8.** Moderation U-shaped Curve between Carbon Damages and Technology Induced Logistics Performance Indices (LPI1 × TMARK).



**Figure 9.** Moderation U-shaped Curve between Carbon Damages and Technology Induced Logistics Performance Indices (LPI2 × TMARK).

Table 6 shows the fair calculation of carbon emissions’ cost due to the country’s economic growth and the moderation effect of technology with LPIs across countries. The results show that carbon damages largely decrease by trademark-induced LPI1, i.e., US\$34,100,000, followed by trademark-induced LPI2, i.e., US\$ 20,200,000, patents-induced LPI1, i.e., 13,800,000, GDP per capita, i.e., US\$15,000,000, and patents –induced LPI2, i.e., US\$61,00,000. The point of interest is that technology-induced LPI1 has a greater magnitude in terms of decreasing the cost of carbon emissions across countries.

During the calculation of losses/gains of carbon damages from GDP per capita, LPI1 × TMAR, and LPI2 × TMAR, it is evident that carbon damages decrease by US\$15,000,000, US\$34,100,000, and US\$20,200,000 which prevents to gain of almost 5.7%, 141.1%, and 42.8% respectively, from the lowest increase in carbon damages. In case of moderation effect of patents with LPI1 and LPI2, it is evident that carbon damages decrease from US\$13,800,000 and US\$6,100,000 that have a share of –2.4% and –56.9% relative to the minimum value of carbon damages, which reduces the cost of carbon emissions about US\$–343239 and US\$–8,043,239 respectively. Table 7 shows the estimates of VAR Granger causality, IRF, and VDA.

**Table 6.** Calculation of Carbon Damages with Technological –Induced Logistics Performance Indices.

Variables	Maximum	Minimum	Range	Cost of Carbon Emissions = Maximum value of Carbon Damages in US\$/Turning Point	GDPPC	LPI1 × PATENTS	LPI2 × PATENTS	LPI1 × TMARK	LPI1 × TMARK	
CDAM	385,000,000,000	14,143,239	3.84,985,856,761							
GDPPC	92,077.57	341.554	91,700			US\$15,000,000	US\$13,800,000	US\$6,100,000	US\$34,100,000	US\$20,200,000
LPI1 × PATENTS	5,535,787	8.160	5,540,000							
LPI2 × PATENTS	5,782,508	7.710	5,780,000							
LPI1 × TMARK	7,618,117	956.450	7,620,000							
LPI1 × TMARK	7,896,506	842.710	7,900,000							
<b>Calculation from Prevention of Losses/Gains from Carbon Damages</b>										
= (Cost of Carbon Damages in US\$)–(Minimum Value of Carbon Damages in US\$)										
OR (formula for calculating estimates in%)										
= [(Cost of Carbon Damages in US\$)–(Minimum Value of Carbon Damages in US\$)]/Minimum Value of CDAM in US\$										
GDPPC	US\$856,761 (5.7%)	LPI1 × PATENTS	US\$–343,239 (–2.4%)	LPI2 × PATENTS	US\$–8,043,239 (–56.9%)	LPI1 × TMARK	US\$19,956,761 (141.1%)	LPI2 × TMARK	US\$6,056,761 (42.8%)	

Note: + shows carbon damages increases, '–' shows carbon damages decreases. CDAM shows carbon damages, GDPPC shows GDP per capita, LPI1 shows logistics of quality services, LPI2 shows logistics of trade and transportation facility, PATENTS shows a total number of patents, and TMARK shows total trademark applications.

**Table 7.** VAR Granger Causality, impulse response function (IRF), and variance decomposition analysis (VDA) Estimates.

Panel-A: VAR Granger Causality										
GDPPC→CDAM	$\chi^2$ value = 6.553 **	PATENTS→CDAM	$\chi^2$ value = 439.515 *	PATENTS→CDAM		$\chi^2$ value = 439.515 *				
IND→GDPPC	$\chi^2$ value = 26.595 *	PATENTS→GDPPC	$\chi^2$ value = 5.377 ***	IND→IFS		$\chi^2$ value = 16.856 *				
GDPPC→LPI1	$\chi^2$ value = 25.204 *	IND→LPI1	$\chi^2$ value = 10.293 *	MHTECH→LPI1		$\chi^2$ value = 16.211 *				
GDPPC→LPI2	$\chi^2$ value = 47.457 *	MHTECH→LPI2	$\chi^2$ value = 13.367 *	<b>CDAM→PATENTS</b>		<b><math>\chi^2</math> value = 4.799 ***</b>				
<b>GDPPC→PATENTS</b>	<b><math>\chi^2</math> value = 8.309 **</b>	MHTECH→PATENTS	$\chi^2$ value = 5.162 ***	CDAM→TMARK		$\chi^2$ value = 99.932 *				
Panel-B: IRF Estimates Response of CDAM										
Period	CDAM	GDPPC	IFS	IND	LPI1	LPI2	MHTECH	PATENTS	TMARK	
1	979,000,000	0	0	0	0	0	0	0	0	
2	815,000,000	31,133,902	11,414,440	-34,231,552	10,391,307	28,750,300	17,798,929	715,000,000	27,489,591	
3	836,000,000	44,423,031	9,741,106	-37,524,336	17,275,727	39,453,430	28,485,206	538,000,000	174,000,000	
4	862,000,000	48,403,079	23,148,686	-31,303,487	8,481,938	34,298,675	35,145,794	616,000,000	282,000,000	
5	885,000,000	47,191,581	28,977,373	-25,077,303	11,590,938	36,444,242	45,351,963	659,000,000	390,000,000	
6	917,000,000	44,041,917	36,270,966	-20,306,564	18,246,204	42,015,507	56,713,288	697,000,000	491,000,000	
7	955,000,000	40,016,487	42,266,737	-16,354,633	28,334,800	50,099,640	69,736,073	734,000,000	584,000,000	
8	1,000,000,000	35,720,069	47,780,292	-13,181,637	41,253,264	59,430,201	84,414,359	765,000,000	668,000,000	
9	1,050,000,000	31,352,273	52,662,917	-10,519,072	56,344,268	69,242,784	101,000,000	793,000,000	743,000,000	
10	1,110,000,000	26,993,592	57,018,365	-8,260,685	73,074,458	79,240,611	119,000,000	817,000,000	810,000,000	
Panel-C: VDA Estimates of CDAM										
Period	S.E.	CDAM	GDPPC	IFS	IND	LPI1	LPI2	MHTECH	PATENTS	TMARK
1	979,000,000	100	0	0	0	0	0	0	0	0
2	1,460,000,000	75.85212	0.045348	0.006095	0.054821	0.005052	0.038670	0.014821	23.94772	0.035353
3	1,780,000,000	73.37281	0.093066	0.007121	0.081591	0.012854	0.075369	0.035681	25.33708	0.984421
4	2,090,000,000	70.08976	0.120948	0.017415	0.081457	0.010946	0.081452	0.054082	27.01669	2.527242
5	2,400,000,000	66.92227	0.130726	0.027854	0.072886	0.010662	0.085051	0.076916	28.11067	4.562959
6	2,710,000,000	63.99801	0.129068	0.039821	0.062825	0.012913	0.090845	0.104276	28.69388	6.868357
7	3,020,000,000	61.35512	0.121113	0.051528	0.053343	0.019158	0.100398	0.136958	28.92033	9.242052
8	3,340,000,000	59.06324	0.110328	0.062510	0.045119	0.030874	0.113598	0.175614	28.85943	11.53928
9	3,670,000,000	57.15358	0.098716	0.072366	0.038210	0.049126	0.129689	0.220861	28.57829	13.65917
10	4,010,000,000	55.63420	0.087370	0.080955	0.032488	0.074451	0.147898	0.273312	28.12958	15.53975

Note: CDAM shows carbon emissions damage, LPI1 shows logistics quality services, LPI2 shows logistics quality in terms of transportation infrastructure and trade, GDPPC shows GDP per capita, IFS shows insurance and financial services, IND show industry value added, MHTECH shows medium and high-tech industry, PATENTS shows total patent applications, and TMARK shows total trade mark applications. \* shows significance at 1% level. \*\* shows significance at 5% level. \*\*\* shows significance at 10% level.

The causality estimates show that carbon damages and GDP per capita both have a bidirectional relationship with patents applications, whereas, GDP per capita has a unidirectional casualty from carbon damages and logistics indices. The result supported the growth-led carbon damages and growth -led logistics performance across countries. The other estimates show a unidirectional causality running from industry value added to GDP per capita, LPI1, and IFS; patents to carbon damages and GDP per capita; medium and high tech industry to LPIs and PATENTS; and CDAM to TMARK. The results supported that industry-led growth, industry-led LPIs, technology-led carbon damages, and high-tech industry led to technical indicators across countries. The IRF estimates suggested that, except for industry value-added, technological factors, medium and high-tech industry, and growth-specific factors are likely to increase carbon damages for the next ten-year time period, whereas, industry value-added will likely minimize carbon damages due to imposition of strong environmental regulations across countries. The VDA estimates suggested that technological factors, i.e., patents and trademark applications, would exert a greater magnitude of 28.129% and 15.539% to influenced carbon damages. At the same time, there is a likelihood that industry value-added will have little effect on carbon damages over a time horizon.

#### 4. Conclusions

The study proposed a smart design for the green supply chain management process aligned with logistics activities and technological factors in moving forward for intelligent and green production. The fuel-efficient technologies are desirable in logistics operations that could lead to a way forward for green development. The study investigated the real cost of carbon emissions influenced by technological factors, logistics activities, and growth-specific factors by using a large sample of countries from 2010 through 2018. The differenced panel GMM estimates show the U-shaped relationship between (i) GDP per capita and carbon damages, and (ii) moderation of technological factors with LPIs and carbon damages. The causality estimates confirmed the technology-led growth, growth-led logistics indices, and technology-led carbon damages across countries. The forecast relationship shows that technological factors, logistics performance indices, and growth specific factors would likely increase carbon damages, while technical factors have a more significant share in influencing carbon damages over a time horizon. The overall results come to the following policy implications:

- Advancement in cleaner production technologies is imperative to reduce the cost of carbon emissions across countries.
- Fuel efficient technologies can be used in logistics operations to improve quality services.
- Logistics operations should be diversified and compliant with all environmental regulations, including ISO-based environmental certifications, ISO certifications for efficient manufacturing units processing, ISO standardization certifications, and ISO certification for clean vehicle transportations.
- Insurance and financial services could expand business opportunities and manufacturers' payoff by transporting their shipments from one place to another place, while the theft and other damages could be covered by efficient insurance services. Financial services' soundness would also create a strong liaison between the financial market and investors to decide on smart production. Hence the process of green supply chain management would be enhanced with technical expertise.
- The cost of carbon emissions is further reduced by sustainable production decisions and high-tech productions, which is a way forward for smart production systems.

These policies enlightened the way towards green supply chain management that is mainly dependent upon resourceful logistics activities, cleaner technologies, sound financial markets, efficient insurance coverage, and quick production processes. All these factors would primarily be needed to go-for-green policies on a global scale.

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## Appendix A

**Table A1.** List of Sample Countries.

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“Albania, Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Bahrain, Bangladesh, Belarus, Belgium, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, Cambodia, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Ecuador, Egypt, El Salvador, Estonia, Ethiopia, Finland, France, Georgia, Germany, Greece, Guatemala, Haiti, Honduras, Hong Kong, Hungary, Iceland, India, Indonesia, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Korea, Kyrgyz Republic, Lao PDR, Latvia, Lebanon, Lithuania, Madagascar, Malaysia, Malta, Mauritius, Mexico, Moldova, Mongolia, Montenegro, Morocco, Mozambique, Namibia, Nepal, Nigeria, North Macedonia, Norway, Oman, Pakistan, Panama, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russia, Rwanda, Saudi Arabia, Serbia, Singapore, Slovak Republic, Slovenia, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Thailand, Trinidad and Tobago, Tunisia, Turkey, Ukraine, United Kingdom, United States, Uruguay, Venezuela RB, Zambia”.

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