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The Impact of Climate Change on Supply Chain Management

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Abstract

Purpose: This study examines the impact of climate change on global supply chain management by analyzing the influence of climate-related variables, specifically CO_2 emissions, temperature fluctuations, and flood-related economic damages, on key logistics performance indicators. These indicators include the customs score, infrastructure score, logistics performance index, and logistics competence and quality score.

Methodology: A mixed-methods analytical approach was employed, incorporating regression analysis, correlation matrix evaluation, and principal components analysis (PCA), supplemented by visual analytics. This methodology enabled the identification of relationships between selected climate variables and supply chain performance metrics across various countries.

Findings: The study reveals a statistically significant positive association between CO_2 emissions and improved logistics performance indicators. This suggests that regions with higher industrial output and consequently higher emissions often have more advanced logistics infrastructure and trade efficiency. Conversely, while flood-related economic damages exhibited a negative correlation with logistics performance, the relationship lacked statistical significance. The findings underscore the complex dynamic between industrial growth, environmental impact, and logistics efficiency.

Unique Contribution to Theory, Practice, and Policy (Recommendations): This research contributes to the theoretical discourse by highlighting the dual role of industrial activity in enhancing logistics performance while exacerbating environmental degradation. Practically, it calls for urgent investment in climate-resilient infrastructure and adaptive logistics strategies. From a policy perspective, the study advocates for integrated climate and trade policies that align economic development with environmental sustainability. Future research should explore indirect and long-term effects of climate change on supply chains to inform more robust mitigation strategies.

Keywords: *Climate Change Impact, Supply Chain Resilience, CO_2 Emissions and Logistics, Climate Risk Management, Sustainable Supply Chain*

1. Introduction

Climate change is now one of the most serious global problems, affecting the economy, environment, and society (Rawat et al., 2024). Global trade, predominantly sustained by intricate supply chain networks, is very sensitive to climate change effects (Hugos, 2024). A supply chain is managing the flow of materials, services, information, and finances from the beginning to the customer. Supply chains are particularly susceptible to the disruptions that climate change introduces (Intergovernmental Panel on Climate Change, 2021). When this complex system faces disruptions, it can lead to problems such as delays, excessive costs, and even lost sales (Hugos, 2024). Figure 1 illustrates various modes of transportation within supply chains, highlighting their vulnerability to climate change-related disruptions.

Figure 1: Illustration of the Impact of Climate Change on Global Supply Chains. Source: Generated by AI using DALL·E 2024

Climate change amplifies vulnerabilities, as discussed in the preceding paragraph, by increasing the frequency and intensity of severe weather events, which disrupt intricate supply chain networks and their reliance on sensitive transportation systems (Rawat et al., 2024; Hugos, 2024; Intergovernmental Panel on Climate Change, 2021). For example, floods may submerge roads and railways, wildfires destroy warehouses and factories, and hurricanes halt port operations (World Economic Forum, 2020) (Figure 2). Increasing numbers of supply chain disruptions worldwide have compelled organizations to improve their risk management systems by incorporating strategies such as diversification of supplier networks, improvement of operational systems, and utilization of advanced technologies, including predictive analytics (Mukwarami et al., 2023). Also, growing expectations from customers and investors push companies to pursue sustainable improvement, demanding a decrease in CO_2 emissions while keeping a lean supply chain (KPMG, 2019).

Figure 2: Different Climate-related Events (Image credit: National Oceanic and Atmospheric Administration, 2023)

1.1. Problem Statement

The intensification of climate change affects the global supply chains and introduces risks to their reliability, speed, and overall performance (Er Kara et al., 2021). Extreme weather conditions, unpredictable temperature changes, and changing regulations increase the vulnerability of corporate supply chain networks to disturbances (Ghadge et al., 2020). Despite increased awareness of these issues, limited understanding exists regarding the global impact of climate change on SCM practices.

This study aimed to address this research gap by examining the extent to which climate change affected the acquisition and production of raw materials in supply chains. Through this examination, the study sought to provide supply chain managers and leaders with guidance for devising adaptive strategies to respond effectively to the challenges posed by climate change

1.2. Research Questions

The research questions for this study are as follows:

- How do climate change factors, such as CO_2 emissions and temperature anomalies, statistically influence key aspects of global supply chain management based on empirical data?
- What are the primary challenges climate change presents to supply chain management, and how do these challenges differ across regions and industries globally?
- How effective are existing supply chain management strategies in mitigating the impacts of climate change, and what specific improvements can enhance their effectiveness?

1.3. Research Hypothesis

- **Null Hypothesis (H_0):** Climate change variables do not significantly impact supply chain performance.
- **Alternative Hypothesis (H_1):** Climate change variables have a statistically significant impact on supply chain performance.

This study investigates the relationship between climate-related factors—CO_2 emissions, temperature anomalies, and flood-induced economic damages—and supply chain performance.

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It uses metrics such as the Logistics Performance Index (LPI), customs score, infrastructure score, and logistics competence score to evaluate this relationship, based on data from global sources like NOAA, Copernicus, Everstream Analytics, and the World Bank.

1.4. Research Objectives

The objectives of this research are as follows:

- To assess the impact of climate change on key aspects of SCM using statistical and visual analytics methods.
- To identify the challenges climate change poses to supply chain management at both global and regional (state) levels.
- To evaluate current strategies used in SCM to mitigate climate change impacts.
- To propose actionable recommendations for enhancing supply chain resilience in response to climate risks.

2. Literature Review

Climate change has become one of the most significant issues worldwide, significantly impacting many fields. As stated by the Intergovernmental Panel on Climate Change, climate change has increased the occurrence and intensity of natural disasters, including hurricanes, floods, and wildfires, which disrupt natural and human systems (McSweeney, R. 2022). These immense economic losses cause agricultural, manufacturing, transportation, and energy disruptions. For example, floods damage food production and lead to food scarcity and price spikes, while hurricanes disrupt structures, halting production or delivery in impacted areas (Cruz & Krausmann, 2013). The supply chain sector is overly sensitive to climatic changes compared with other sectors because it consists of extensive supply chain networks spanning various global regions. In addition, the operations of supply chains are highly integrated, and any disruption within one part of the supply chain can quickly cascade across the entire system, manifesting delays, heightened costs, and operational inefficiencies. Climate risks, including rising sea levels, unusual temperature extremes, and rainfall changes, affect routes for transport, storage locations, and production facilities (Sarkis et al., 2020). For instance, rising sea levels and stronger storms can flood coastal ports (Figure 3), disrupt logistics, and increase rerouting costs (Leung et al., 2023). Also, Figure 4 illustrates the devastating effects of climate change on agriculture, with droughts leading to barren farmlands and diminished crop yields, posing significant challenges to global food supply chains

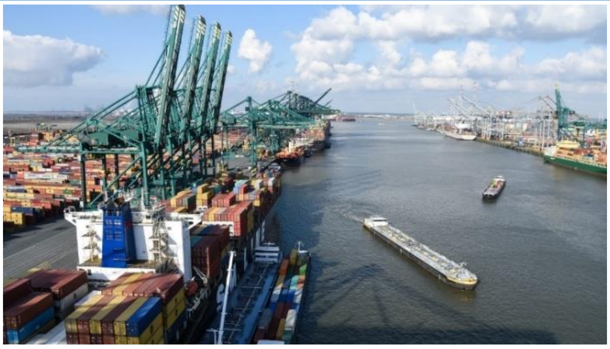

Figure 3: A Flooded Port Showing the Effect of Rising Sea Levels on Supply Chains (Image credit: Asariotis, 2021)

Similarity, a drought in a large production area cuts down the supply of raw materials for food production, and supply chains around the globe could be impacted (Kanike, 2023). Likewise, adverse weather conditions affect production in manufacturing countries, causing shortages and raising product prices worldwide. Unexpected events in global supply chains have received much attention, especially after the COVID-19 health crisis, during which external disruptions caused severe disruptions to global supply chains (Ivanov & Dolgui, 2021).

Figure 4: Drought-Stricken Farmland Highlighting the Impact of Climate Change on Agricultural Supply Chains (Image credit: Saadi, 2022)

Due to the rise of climate change and its implications for natural disasters and disastrous climatic occurrences, there is a realization that climatic risks must be integrated into SCM (Rüttinger et al., 2020). This involves improving the infrastructure's durability, expanding the available supply sources, and monitoring and predicting measures that can recognize probable interferences in the provision. Nevertheless, the existing research has left room for improvement in identifying concrete approaches and measures suitable for tackling these problems. This research, therefore, seeks to add to this body of knowledge by discussing the effects of climate change on SCM, discussing some of the challenges that are associated with climate change effects on SCM, and assessing the effectiveness of the strategies that have been proposed to improve the resilience of an organization to climate change.

2.1. Previous Research on Supply Chain Disruptions

Global supply chains have recently been exposed to many risks, including natural disasters, climate change, and other unexpected events. These disruptions might critically reduce the performance and resilience of supply chains, hence requiring the implementation of strategies that may reduce such effects. Thus, research on supply chain disruption has become quite critical.

A central focus of research has been the intersection between climate change and SCM. Ghadge et al. (2020) thoroughly reviewed the risks associated with climate change in global supply chains.

The research successfully identified the considerable influence that extreme weather events can have on supply chain operations. The authors introduced a new framework by emphasizing the need for a systems theory-driven approach to risk management within supply chains. The study underscored the relationship between climate and supply chain dynamics, highlighting the close interconnection between natural disasters and greenhouse gas emissions. Recent studies emphasize the growing impact of climate change on supply chains and the urgent need for resilience. Godde et al. (2021) highlighted how climate instability threatens food security, while Ojo (2024) and Katsaliaki et al. (2022) stressed adaptive risk management, stakeholder collaboration, and technological innovation as key resilience strategies. Pankratz and Schiller (2024) linked climate risks to supplier performance and customer behavior, noting financial consequences. Azadegan et al. (2020) demonstrated the value of business continuity programs in boosting preparedness and economic outcomes. Collectively, these works underscore the critical role of climate adaptation, continuity planning, and resilience in modern supply chain management.

2.2. Visual Analytics in Supply Chain Management

In today's complex supply chain landscape, visual analytics plays a vital role in addressing disruptions, particularly those caused by climate change. By combining data visualization tools (e.g., dashboards, heat maps, flow charts) with analytical methods, visual analytics helps identify patterns, improve decision-making, and enhance supply chain resilience (Maheshwari et al., 2021; Bui et al., 2021). Dashboards offer real-time insights into KPIs such as inventory levels, order status, and transportation (Nabil et al., 2023). These tools allow managers to detect stock imbalances and make informed decisions.

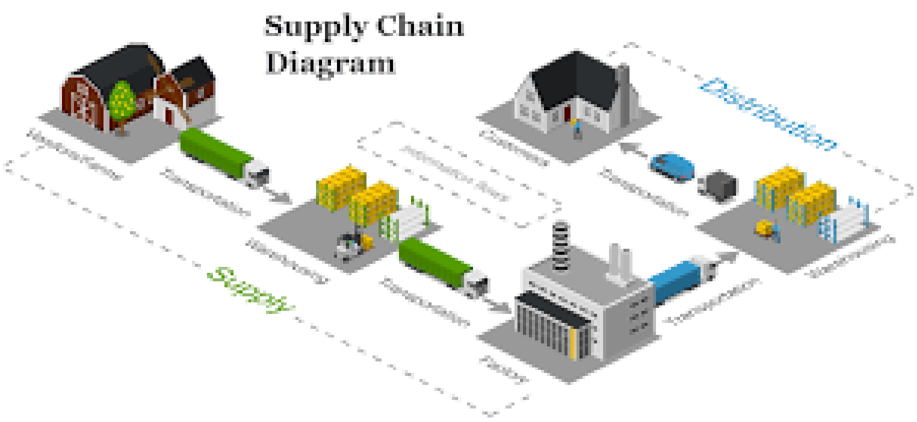

Figure 5: Supply Chain Flow Diagram (Icograms, 2024)

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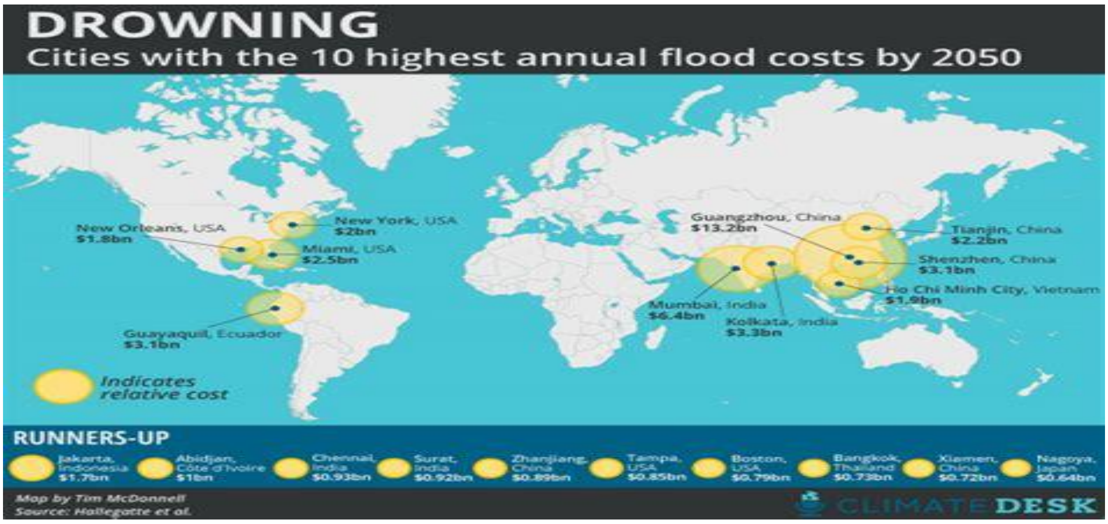
Key applications include:

- ❖ **Inventory Flow Disruption:** Climate events (e.g., floods, wildfires) impact storage and transport, causing fluctuations in product availability.
- ❖ **Cost Implications:** Dashboards highlight financial impacts like emergency sourcing and shipment delays.
- ❖ **ABC Classification:** Prioritizes critical inventory to manage supply risks linked to environmental events.
- ❖ **Gross Inventory & Revenue:** Tracks turnover and profitability under climate pressure (e.g., overstocking to hedge against shortages).
- ❖ Sustainability: Visual analytics supports identifying greener practices for long-term resilience.
- ❖ **Strategic Planning:** Enables data-driven actions such as supplier diversification, warehouse relocation, and infrastructure investments.
- ❖ Overall, visual analytics empowers supply chains to remain agile, efficient, and sustainable amid climate challenges.

Beyond dashboards, **heat maps** help visualize demand density, warehouse locations, and transport routes—enabling managers to reroute or reschedule operations to avoid delays (Bellini et al., 2024). **Flow charts** illustrate the movement of goods and information, highlighting inefficiencies and opportunities for process optimization (MacCarthy et al., 2022).

Predictive analytics uses visual tools like line graphs and trend charts to forecast demand, detect supply risks, and prepare for disruptions (Pawar & Paluri, 2022). Scenario analysis, via decision trees or simulation models, helps managers evaluate alternatives and select the most resilient supply chain strategy (Shokouhyar et al., 2021).



Visual analytics supports effective supply chain risk management by identifying areas vulnerable to supplier failure, transportation disruptions, or natural disasters (Mehdizadeh, 2021). Geospatial analysis provides regional insights into risks like natural hazards and geopolitical instability (Scott, 2023), while visualization helps organizations plan for localized disruptions. Tools such as Tableau enable real-time, interactive dashboards for monitoring KPIs and supplier performance (Leal, 2019). Additionally, the Supply Chain Risk-Value Matrix categorizes suppliers by risk and value, aiding in strategic decision-making and resource allocation. By integrating such tools, organizations enhance resilience, optimize operations, and gain a competitive edge in complex supply chain environments.

2.3. Research Gap

While prior research has explored climate change impacts on supply chains, it often lacks robust, data-driven analysis and overlooks regional and industrial differences. Existing studies tend to generalize climate risks and rarely apply advanced analytics or technologies to assess supply chain resilience. This study addresses these gaps by using statistical and visual methods to analyze the effects of CO_2 emissions, temperature anomalies, and flood-related damages on supply chain performance. Drawing from reputable data sources like NOAA, the World Bank, and Everstream Analytics, the study leverages PCA and visual analytics to provide actionable, region-specific insights and recommend strategies for improving supply chain resilience amid climate change.

2. Data and Methodology

2.1 Data Sources

This study analyzes the impact of climate change variables on global supply chain performance using a multi-source dataset. Independent variables include annual CO_2 emissions per capita, temperature anomalies, and flood-related economic damages (as a share of GDP). Dependent variables comprise the Logistics Performance Index (LPI) and its subcomponents: Customs Score, Infrastructure Score, and Logistics Competence and Quality Score. Climate data were sourced from NOAA (2024), supply chain performance indicators from the World Bank's LPI dataset (2024), and flood damage data from Everstream Analytics (2024).

2.2 Data Preprocessing

The initial dataset contained 561 observations and 13 variables. After removing missing values and redundant columns (e.g., categorical rankings, duplicate flood metrics), the final cleaned dataset included 398 complete observations for analysis. Missing data were omitted to maintain model integrity and prevent bias.

All variables were normalized using Min-Max scaling to ensure comparability across units and reduce the effect of extreme values:

$$X_{\text{normalized}} = \frac{X - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}}$$

This normalization preserves the original data distribution while enabling robust regression modeling.

Tbale 1: First and Last 10 Rows of Combined Preprocessed Dataset

Year	Country	LPI Score	LPI Grouped Rank (*)	Customs Score	Infrastructure Score	International Shipments Score (*)	Logistics Competence and Quality Score	Tracking and Tracing Score (*)	Timeliness Score (*)	Annual CO2 emissions (per capita)	Total economic damage as a share of GDP - Flood	Temperature anomaly
2007	Netherlands	4.177695149	2	3.99225	4.29032	4.04878	4.25	4.13636	4.38235	10.538973		0.6809682
2007	Germany	4.098695236	3	3.88279	4.19133	3.90984	4.20728	4.11864	4.32727	10.472896	0	0.6292377
2007	Austria	4.062573643	5	3.83333	4.06061	3.96667	4.13333	3.96552	4.44444	8.935539		0.5736909
2007	Japan	4.023554099	6	3.78648	4.10638	3.76557	4.11985	4.07605	4.34454	10.177901	0	0.3161912
2007	Switzerland	4.016196383	7	3.84848	4.13333	3.66667	4	4.03571	4.48	5.7495914	0.07132076	0.3355184
2007	United Kingdom	3.993361748	9	3.739	4.04938	3.85209	4.01954	4.1	4.24815	9.134187	0.27335292	0.383963
2007	Canada	3.921925946	10	3.81818	3.94898	3.77895	3.85393	3.97778	4.18824	18.06789	0	-0.247153
2007	Belgium	3.893763601	12	3.61261	4	3.65094	3.94949	3.95918	4.25301	11.307179		0.4795012
2007	Denmark	3.859046038	13	3.97143	3.82353	3.66667	3.83333	3.75862	4.11111	9.983965		0.6423784
2018	Somalia	2.208677	144	2	1.812865	2.612865	2.304539	2.23311	2.204196	0.041368622	0.9663922	-0.121682
2018	Cuba	2.197159	146	2.029672	2.041667	2.270412	2.202441	2.14689	2.462494	2.0420773		0.1360966
2018	Iraq	2.176271	147	1.839437	2.0335	2.324812	1.908431	2.19153	2.719949	4.526985	0	0.9972141
20	Papua	2.1741	148	2.32	1.97076	2.14723	1.8827	2.257	2.436	0.8153		0.261

Note. Variables marked with an asterisk () are not included in the regressions analysis and are included for reference or categorization purposes only.

Table 1 displays the first and last 10 observations of the preprocessed dataset, originally consisting of 561 observations and 13 variables, including logistics performance metrics (LPI Score, Customs Score, Infrastructure Score), climate factors (Annual CO_2 Emissions, Temperature Anomalies), and flood-related economic damages. During preprocessing, irrelevant or redundant columns—such as indexing variables, grouped rankings, and duplicate flood metrics—were removed to enhance analytical clarity. A new column was added to capture flood-related damages, while 163 rows with missing values in key variables were excluded to maintain data integrity.

The final dataset, reduced to 398 complete records, includes essential independent variables (CO_2 Emissions, Temperature Anomalies, Flood Damages) and dependent variables (LPI Score and its subcomponents). Flood damages were consolidated into a single metric (economic losses as a share of GDP) to improve analytical consistency and model accuracy.

.3 Descriptive Statistics

Table 2: key descriptive statistics for the main variables used in the analysis.

Variable	Mean	Median	Std. Dev.	Variance
LPI Score	2.82	2.71	0.55	0.3
CO_2 Emissions (per capita)	3.62	1.60	4.94	24.44
Temperature Anomaly	0.25	0.23	0.44	0.19
Flood-related Economic Damage (%)	0.11	0.00	0.46	0.21

Note: CO_2 emissions show high variability reflecting industrialization differences, while flood damages are highly skewed, with severe impacts concentrated in a few regions.

4. Results

This section presents the core findings of the study, analyzing the relationship between climate change variables and supply chain performance.

4.1 Correlation Analysis

Correlation matrices indicate strong intercorrelations among LPI subcomponents ($r = 0.78$ to 0.92), justifying their aggregation into a composite LPI Score. Independent climate variables showed negligible correlations, suggesting distinct climate phenomena without multicollinearity.

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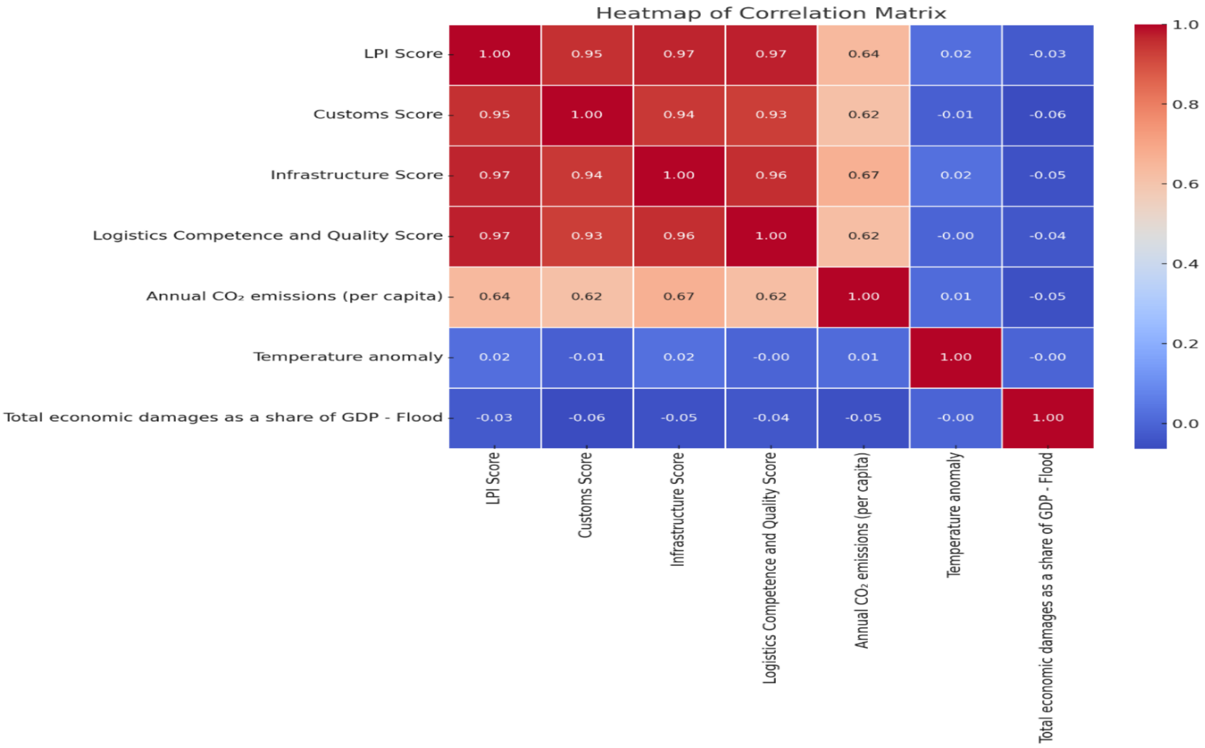

Figure 13: Correlation Matrix of Variables

4.2 Principal Component Analysis (PCA)

PCA was conducted to address multicollinearity among dependent variables, resulting in a single principal component (PC1) that explained over 85% of the variance across LPI subcomponents. PC1 was used as the composite measure of supply chain performance in subsequent regression analyses.

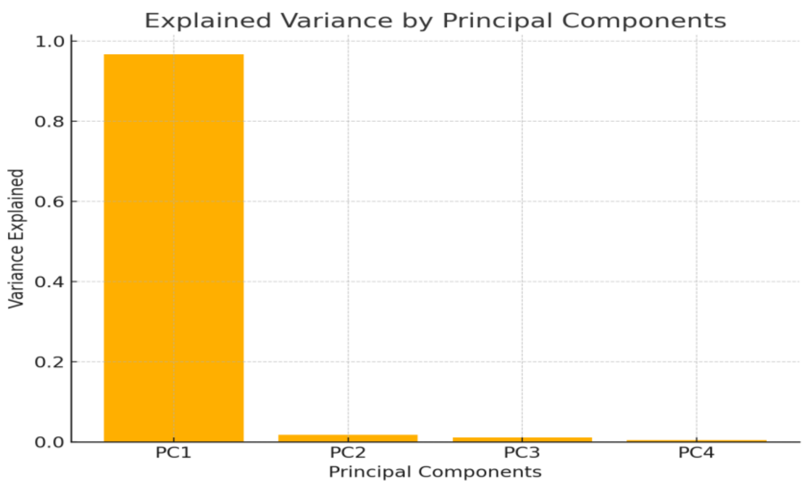

Figure 14: Explained Variance by Principal Components

4.3 Regression Analysis

A multiple linear regression model assessed the impact of CO_2 emissions, temperature anomalies, and flood-related economic damages on the LPI Score. Key model statistics are summarized in Table 3.

Metric	Value
F-Value	90.67
R-Squared	0.408
Adjusted R-Squared	0.404
p-Value	<0.001

CO_2 emissions showed a significant positive relationship with LPI (coefficient = 0.35, $p < 0.001$), indicating that industrialization enhances logistics infrastructure. Temperature anomalies and flood damages were not statistically significant ($p > 0.05$).

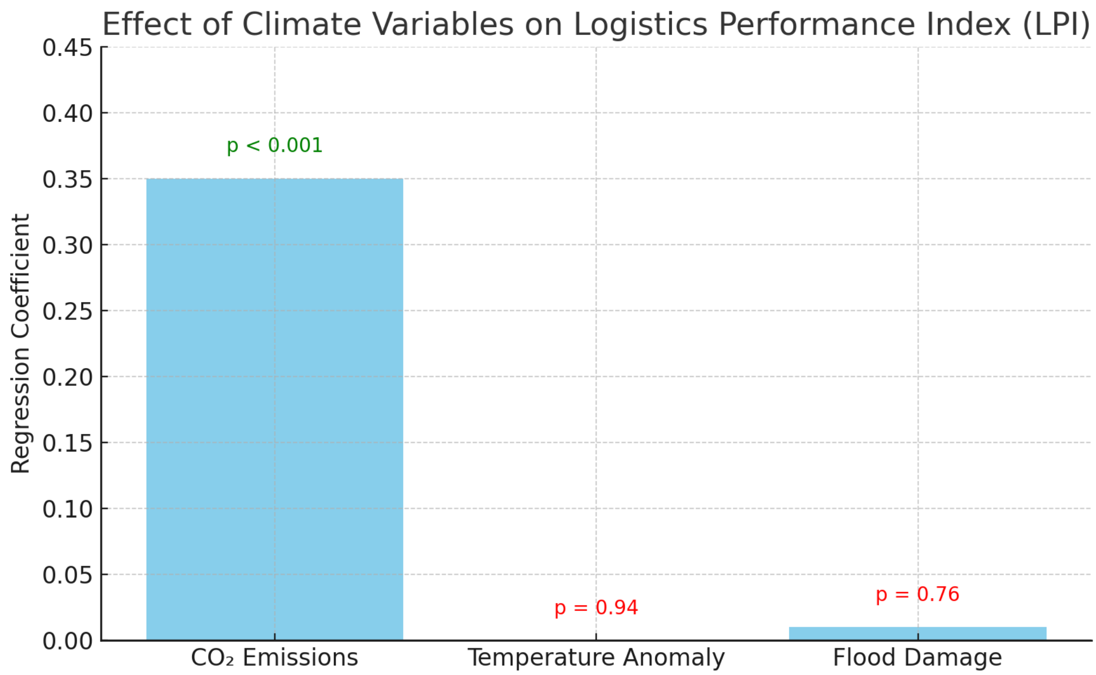

Figure 3: Regression model summary: Effect of climate variables on Logistics Performance Index (LPI).

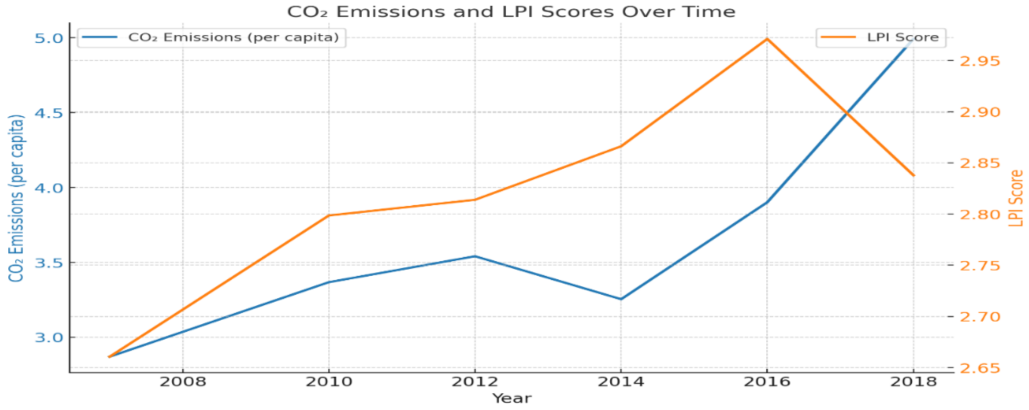

Figure 16: CO_2 Emissions and LPI Scores Over Time

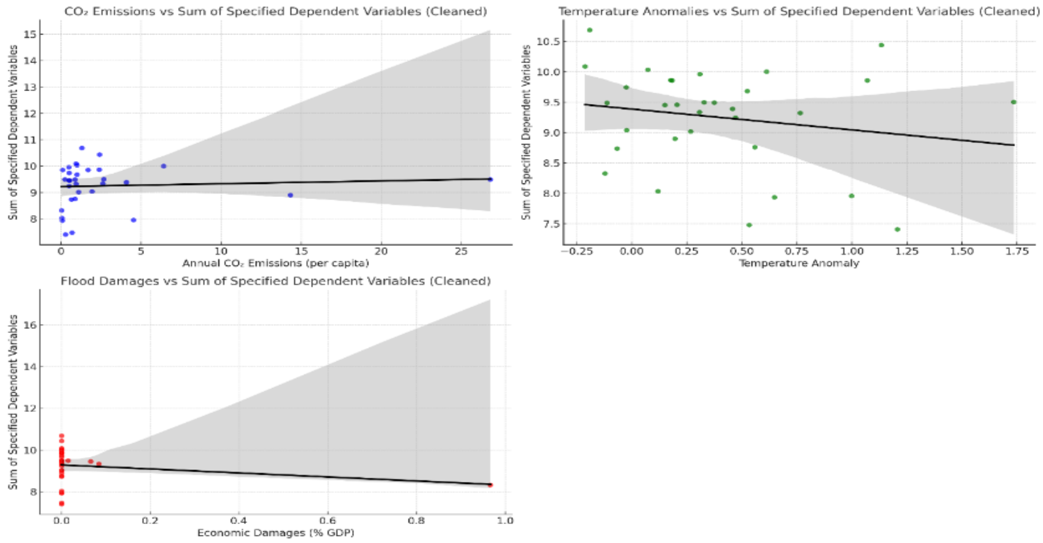

Figure 17: Scatterplots Illustrating the Relationships Between Climate Variables and Supply Chain Performance

4.4 Summary of Findings

- **CO_2 Emissions** positively impact supply chain performance, likely due to concurrent industrial and infrastructure development.
- **Temperature Anomalies and Flood Damages** showed no significant effect on global supply chain efficiency in this aggregated analysis, suggesting potential localized or delayed impacts.
- The model explains approximately 40.8% of variability in logistics performance, indicating that additional factors beyond climate variables contribute to supply chain resilience.

5. Discussion

This study examined the influence of climate change variables, including CO_2 emissions, temperature anomalies, and flood-related economic damages, on global supply chain performance, measured by the Logistics Performance Index (LPI). The findings reveal a nuanced relationship between environmental factors and logistics efficiency.The positive and statistically significant association between CO_2 emissions and LPI indicates that regions with higher industrial activity tend to exhibit stronger supply chain infrastructure and logistics capabilities. This aligns with prior research suggesting that industrialization drives improvements in transport networks, customs efficiency, and logistics competence, which collectively enhance supply chain performance. However, this relationship also highlights a paradox: while industrial growth supports logistics efficiency, it simultaneously contributes to increased greenhouse gas emissions and long-term environmental risks.

In contrast, temperature anomalies and flood-related economic damages showed no statistically significant effects on global supply chain performance in this study. This may reflect the aggregated nature of the data and suggest that such climate disruptions have more localized or sector-specific impacts that are not easily captured in global-level indices. Additionally, modern supply chains may exhibit some resilience to short-term climate shocks through redundancy, diversification, and adaptive strategies, thereby mitigating immediate performance degradation.

The model's explanatory power, accounting for approximately 40.8% of the variance in logistics performance, implies that while climate factors are important, other drivers such as workforce skills, technological advancements, regulatory environments, and economic policies also play critical roles in shaping supply chain efficiency.

This study has important practical implications. Policymakers should recognize the dual challenge of supporting industrial growth to enhance logistics infrastructure while pursuing sustainable development goals to limit emissions and mitigate climate risks. Businesses are encouraged to invest in climate-resilient logistics systems, green technologies, and adaptive supply chain management practices to prepare for future environmental uncertainties.

Limitations of the study include the reliance on aggregate global data, which may mask regional heterogeneity and the lagged effects of climate impacts. Future research should incorporate more granular, longitudinal datasets and explore additional climate-related risks, such as extreme weather events and supply chain disruptions, to better understand their complex dynamics. Furthermore, integrating machine learning techniques could enhance predictive insights on the long-term interplay between climate change and supply chain resilience.

Overall, this research contributes to the growing body of knowledge on climate change's role in global supply chains and underscores the urgent need for integrated strategies that balance economic development with environmental sustainability.

6: Conclusion

This study explored how climate change impacts global supply chain performance by examining CO_2 emissions, temperature anomalies, and flood-related economic damages. The findings revealed a positive correlation between CO_2 emissions and logistics efficiency, underscoring the short-term benefits of industrialization but raising concerns about long-term sustainability—highlighting what the authors term the "industrialization paradox." While temperature and flood variables showed no immediate statistical impact, their cumulative and region-specific effects merit further theoretical investigation. Practically, the integration of visual tools such as box plots and scatter plots enhanced understanding by identifying outliers and nonlinear trends, offering deeper insights for supply chain strategists. The study offers clear policy implications, recommending carbon pricing, climate-integrated trade policies, and mandatory climate risk assessments. Businesses are advised to invest in low-carbon technologies, predictive analytics, and diversified sourcing strategies. Future research should prioritize long-term, regional, and AI-driven models to further understand and manage climate risks in logistics networks.

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