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Emission Trajectories in the Trade Context: A Comprehensive Machine Learning Approach Using K-Means and ARIMA

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ABSTRACT

ARIMA modeling, K-means clustering, and Correlation analysis are applied in this study to predict "emission per capita" and "merchandise trade" as percentage of GDP for 10 developed countries. The objective is to recognise and forecast trends in emissions and trade flows, and to cluster countries with similar emissions, population and trade activity. Countries were categorized into three clusters according to output of K-means clustering based on mean per capita emissions (mean emissions per capita range from 2.1 to 9.8 metric tons per capita) and merchandise trade as percentage of GDP (20% to 55%). An ARIMA model was then built for each cluster to predict future trends in emissions. For Cluster 1 (low-emission countries), emissions reductions are anticipated to fall between 1.5% and 3.2% in the next 10 years; for Cluster 2 (moderate-emission countries), between 2.0% and 4.5%. Cluster 3 (high emissions) will lower emissions by between 0.5 and 2.1%. Results reveal how trends in emissions are likely to change over the next 10 years for groups of countries associated with similar levels of activity. It highlights the performance of clustering methods for prediction of environmental economics - a critical topic with ramifications for decision-making in emissions reduction and trade.

INTRODUCTION

In the current era of globalization, trade between countries has become the key source of economic growth and development (Chen & Liu, 2024; Rasshyvalov *et al.,* 2025). Merchandise trade, the import and export of physical goods, accounts for a significant proportion of the global GDP of industrialized nations. It rose by almost 9.5 percent over 2017, which was 35.2 trillion US dollars. The total trade in goods reached 38.6 trillion US dollars in 2018 ("World - International Merchandise Trade," 2020). Such a considerable increase demonstrates the significance of the global merchandise trade, and their potential effect on GDP as well. But trade has very negative environmental consequences despite, or because of, it promoting economic development. Given that transportation is a major contributor to greenhouse gas emissions, one of the most pressing problems is the increasing carbon emissions due to transporting goods across international boundaries. Dlamini *et al.* (2024) demonstrated that trade has resulted in a significant and positive impact on regional emissions, implying that the increase in trade is associated with the increase in nations' carbon footprint. Finding a balance between carbon emissions and merchandise trade is critical for achieving sustainable growth, but much study is needed to understand the trade-offs involved. According to Abbass *et al.,* (2025), financial development actually leads to a 1.25 percent decrease in CO_2 emission. carbon emissions trading from a global perspective, can solve environmental problems and motivate the development of the economy in cities by furthering green technological innovation (Zou *et al.,* 2025). This will be important to push through more decisive, progressive laws on the planet and green operational practices worldwide.

Air pollution and global warming due to climate change are associated with emissions of carbon dioxide (CO_2), mainly originating from fossil fuel activities such as transport (Jain & Rankavat, 2023). But with rising trade volume, it takes a toll on the environment — particularly when supply chains stretch across multiple continents (Shamout, 2024). Using a panel of ten developed nations for the last half-century (1970–2020), this study investigates the relationship between carbon emissions per capita and merchandising trade (as a share of GDP). It further explores this relationship to better understand how trading characteristics shape environmental outcomes, thus informing potential sustainable supply chain strategies.

Research Questions

This study examines the relationship between global trade and the state of the environment, in particular, per capita carbon emissions. The main research questions in this study are:

RQ1: What is the relationship between per capita carbon emissions and merchandise trade?

RQ2: How countries trade and how it is responsible for carbon emission?

RQ3: Can the amount of trade and amount of emissions be used to cluster different countries?

RQ4: Is it possible to model previous trends to forecast future carbon emissions based on time-series?

This study will examine whether the higher trade volumes are associated with more carbon emissions by addressing

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these research questions. It will also explore potential ways countries could mitigate their environmental impact.

Objectives of the Study

To explore the link between merchandise trade and carbon emissions the main objectives of the current study are as follows:

1) Check whether a statistical correlation exists between the trade volume and emissions to provide empirical evidence of their interdependence.

2) Determine trends in carbon emissions and trade activity over the past 50 years for a number of different countries.

3) Using historical trade and emission data, employ advanced time-series models such as ARIMA to forecast the future carbon emissions of developed countries.

4) Investigate trade-emission relationships by grouping nations into trade clusters.

LITERATURE REVIEW

Different literatures have examined many aspects of the connection between carbon emissions and global trade, including industrialization, trade liberalization, and environmental sustainability. The research shows that increased trade often means more carbon emissions as it uses more energy to transport and produce (Monkelbaan, 2024). This is mostly due to the fact that as countries increase their engagement in international trade, they tend to raise their output to meet the demands of overseas markets (Awais *et al.,* 2024). Liu (2023) found that China's shifting trade patterns encourages factor mobility—with the potential to increase production and, consequently, carbon emissions. Similarly, Valodka *et al.* (2020) showed that trade liberalization was shown to impact carbon emissions in the textile sector. Zhao *et al.* (2023) claimed that trade increases emissions and we should consider trade-driven production growth more holistically. However, studies also show that trade can promote energy efficiency in production processes and help spread green technologies (Fu, 2023; Liu *et al.,* 2022). As a result, cap-and-trade policies are now a new tool governments are wielding against businesses to motivate them to invest more in energy-saving technologies. Zheng *et al.* (2018) claimed that these policies have proved successful in boosting and protecting the deployment of green technologies. Environmental impact studies and debate on economic globalization focused on the link between trade and emissions. Zhao *et al.* (2020) discussed China's efforts to incentivize companies to use renewable energy and develop a carbon trading market. It showed a model that advocates for stricter laws and greater productivity. Another research investigated the relationship among energy use, carbon emissions and technological progress in 179 countries from 1980 to 2019. But they stressed the importance of technology in reducing energy consumption. In support of the belief that developed nations can lower emissions while boosting trade through improved technologies and regulations, they emphasized the role that technology plays in enhancing energy efficiency and lowering emissions (Bibi *et al.,* 2022). Study conducted by Ali *et al.* (2021) supported the notion that industries can isolate trade growth from emissions by focusing on the role of eco-innovation, thereby showcasing the potential for improved sustainability and efficiency in developed nations. Su *et al.* (2021) emphasized that despite this progress, stricter environmental laws and standards in developed nations are required to achieve similar outcomes, and also emphasized targeted policies that leverage technology for sustainable development. The energy implementation of a resource-rich economy is based on fossil fuels, and its industrial structure is productivity-oriented, so the emissions of resource-exporting economies often grow sharply (Pham *et al.,* 2023). Another research highlighted that fossil-fuel emissions consistently increasing climate forcing over time (Tubiello *et al.,* 2013). Research suggested that demographic shifts impact urbanization, industrial activity and energy demand, making population trends an important part of emissions trajectories (Baschieri & Snow, 2024; Pan *et al.,* 2024). Using a broad analytical approach, Thi Mai *et al.* (2024) discovered a positive correlation between increasing population and rising CO_2 emissions, particularly in urban areas, highlighting the connection between environmental impact and demographic changes. STIRPAT model was adopted to explore the impact of different types of urbanization and identified a notable positive relationship between population urbanization and increasing carbon pollution (Y. Zhao *et al.,* 2022). The modelling allowed an intimate view of how energy and demographic trends interact, revealing that a substantial fraction of the required reduction in emissions could play a major role in meeting the 2050 targets (O'Neill *et al.,* 2010). While urbanization and transport create emissions, efforts in most cities are being embraced to create opportunities to save through smart infrastructure and policy (Jin *et al.,* 2019; Zeng *et al.,* 2022; Zheng, 2021; Zhong *et al.,* 2022). While urban cities produced 55% of emissions and consumed 62% of global energy use, they also provided opportunities to reduce carbon output via better infrastructure and the potential for public participation, according to Preston *et al.* (2020). A different area of interest relates how trade-emission relationships affected by energy sources. Studies have examined the difference in emissions between diversified and renewable energy economy and one that depends mainly on coal and fossil fuels (Fareed *et al.,* 2021; Farhani & Ozturk, 2015). Fatima *et al.* (2022) explored the differences in emissions profiles between renewable energy-dependent economies and non-renewable economies. Rehman *et al.* (2021) noted renewable energy economies have negative correlations to greenhouse gas emissions while coal and fossil fuel economies have emissions that are through the roof. Another study on Bahrain's sectoral energy and carbon intensity found that industrial sector being the most emitting sector which is consistent with the Environmental Kuznets Curve (EKC) (AlSabbagh, 2025). Sarkodie *et al.* (2019) stressed the importance of broadening renewable energy sources to reduce emissions. There are many studies on how the transition to cleaner energy can reduce emissions for economies with high levels of trade, and there is evidence that policies promoting the use of renewable energy are working (Hu *et al.,* 2020; Lin *et al.,* 2019). In environmental economics, regression models, especially OLS, have been widely employed to examine how trade, population influences emissions (Lin *et al.,* 2019; Peters *et al.,* 2011). Other research had found that non-trade factors combine in a way that influences emissions levels. S. Ali *et al.* (2020) used multiple regression and time series analysis techniques to show that a variety of factors, such as population dynamics and economic growth, have an impact on carbon emissions in addition to trade. A further study analyzed 17 variables, ranging from energy prices and macroeconomic indicators, ecological factors, to demonstrate the complexity of emissions pricing (Y. Liu, 2024). This suggests that industrial efficiency, regulations, and technological adoption significantly influence emissions trends, even though trade is a contributing factor. Predictive models like ARIMA were used to predict future emissions trends, with studies confirming that stringent environmental regulations, carbon pricing mechanisms, and the transition to renewable energy sources will almost certainly lead to the gradual decrease of emissions in developed countries (Z. Li, 2023; Rahman & Hasan, 2017). This study adds to the discussion by highlighting the numerous relationships between trade and emissions. Future studies can analyze the impact of changes in the supply chain, technological advances and green technologies to mitigate the amount of carbon emissions generated by trade.

MATERIALS AND METHODS

Data Collection

The study's data included ten developed nations—Australia, Japan, France, Germany, Canada, Italy, Spain, South Korea, the United Kingdom, and the United States—from 1970 to 2020. The main variables in this study are:

1) CO_2 emissions per annum: The annual consumption of CO_2 is available in tons of CO_2 from Our World in Data (Friedlingstein *et al.,* 2023).

2) Trade in merchandise as percent of GDP: Depth of survey is obtained from The World Bank Data, – indicates how much a country's GDP is affected by trade in goods (World Bank Group, 2023a).

3) CO_2 emissions per capita are based on population (also sourced through World Bank Data) as a potential third explanatory variable (World Bank Group, 2023b).

Analytical Techniques

The analysis was conducted using the following techniques:

Pearson Correlation

Pearson correlation measures the linear relationship between two variables. It quantifies the degree to which a change in one variable will create a change in another variable, ranging between −1 (perfect negative correlation) and +1 (perfect positive correlation) (Weisburd *et al.,* 2020). To examine the relationship between per capita carbon emissions and merchandise trade, the Pearson correlation coefficient was calculated for each respective country. The correlation values indicated whether trade growth is associated with increased emissions.

Descriptive Statistics

Statistics such as mean and quartile values were calculated for trade as a proportion of GDP and carbon emissions per capita. The results identified the top and bottom three countries in each category, providing insights into the areas with highest and lowest emission and trade intensity.

Data Visualization

Compared emissions and trade for every nation in a single graph to have greater understanding of the links and patterns in the data. To do so, a stacked bar chart was used. Time-series analysis was conducted for trade as well as emissions in order to present an overview of how they have evolved through the last 50 years (Le, 2024) .

OLS Regression

Ordinary least squares (OLS) regression is one method for estimating a linear regression model's parameter. It minimizes the total squared differences between the predicted and the actual observed values (Shoukat *et al.,* 2024). Ordinary Least Squares regression model analyses the impact of population and merchandising trade with dependence to CO_2 emissions. Such model helps to estimate how much population and trade impact emissions among countries.

K-means Clustering

K-means clustering is an unsupervised machine learning technique that is used to divide a dataset into K different, nonoverlapping groups or clusters. Every point gets assigned to the cluster with the closest mean, which helps to minimize the variance in each cluster (Khan *et al.,* 2024). This form of unsupervised learning helps to identify countries with similar trends for both variables, providing additional insights into trade and emission trends.

ARIMA Forecasting

ARIMA is a statistical model used in time series forecasting. It employs differencing (I), periodic (AR), and moving average (MA) terms to ensure that the sequence is stationary. It is one of the statistical model utilized for prediction of future points in a time series based on previous data (Hafiz Muhammad Zeeshan Raza *et al.,* 2024). The ARIMA model was used to forecast future CO₂ emissions from 2021 to 2031. Based on past patterns, this model aids in forecasting the country' emissions trajectory.

Linear Regression

Linear regression is a statistical method for modeling the relationship between a dependent variable and one or more independent variables, which is fit with a linear equation to the observed data. It is commonly utilized in predictive modeling due to its assumption that the relationship between the variables can be depicted by a straight line (Pawar *et al.,* 2024). A simple regression was conducted on all points in the data relating to CO₂ emissions and merchandise trade to obtain the direct relationship between the two variables.

RESULTS AND DISCUSSION

Pearson Correlation between Trade and Annual CO₂ Emission

Pearson correlation coefficients were computed to analyze the relationship between CO₂ emissions per capita and merchandise trade (as a percentage of GDP). For Australia (r = 0.9097, p = 2.4773e-20) and Canada (r = 0.7808, p = 1.4088e-11), the figures showed a strong positive correlation, indicating that the more trade activity the two countries engaged in, the greater their carbon emissions. On the other hand, significant negative correlations were observed for France (r = -0.6573, p = 1.6130e-07) and Germany (r = -0.8705, p = 1.0588e-16), suggesting that increased trade did not necessarily lead to increased emissions. Japan (r = 0.2207, p = 0.1197) and Italy (r = 0.1163, p = 0.4162) showed low correlations, indicating no significant relationship. These results showed that trade-emission dynamics are complex: upstream industrial composition, downstream energy mix, and environmental policies of both exporters and importers matter.

Pearson Correlation between Annual CO₂ Emission and Population

Pearson correlation coefficients were calculated to explore the relationship between annual CO₂ emissions and population. The research also showed strong positive correlations between population growth and increased carbon emissions in Canada (r = 0.9253, p = 2.8758e-22), Australia (r = 0.9558, p = 1.0420e-27) and South Korea (r = 0.9732, p = 6.0280e-33). Although to differing degrees, the United States (r = 0.6926, p = 1.7941e-08), Spain (r = 0.6939, p = 1.6421e-08) and Japan (r = 0.8762, p = 3.7746e-17) also showed favorable connections. On the other hand, France (r = -0.8613, p = 5.0669e-16), Germany (r = -0.8326, p = 3.5896e-14), and the UK (r = -0.9073, p = 4.6088e-20) showed high negative correlations, indicating that emissions did not always increase with population growth, possibly due to advancements in green technology and environmental regulations (Dehdar *et al.,* 2022). Italy was not significantly associated with a low correlation (r = 0.1262, p = 0.3777). These values are presented in Table 1.

Table 1: Pearson Correlation Values

Country	**Trade and Annual CO₂ Emissions**		**Population and Annual CO₂ Emissions**	
	Correlation	**P-value**	**Correlation**	**P-value**
Australia	0.9097	2.4773e-20	0.9558	1.0420e-27
Canada	0.7808	1.4088e-11	0.9253	2.8758e-22
France	-0.6573	1.6130e-07	-0.8613	5.0669e-16
Germany	-0.8705	1.0588e-16	-0.8326	3.5896e-14
Italy	0.1163	0.4162	0.1262	0.3777
South Korea	0.5748	1.0275e-05	0.9732	6.0280e-33
Spain	0.7364	7.3556e-10	0.6939	1.6421e-08
United States	0.7609	9.2163e-11	0.6926	1.7941e-08
Japan	0.2207	0.1197	0.8762	3.7746e-17
United Kingdom	-0.3111	0.0263	-0.9073	4.6088e-20

Ranking Based on CO₂ Emission and Trade

To gain additional insight, statistics such as mean, quartile values, and ranking of countries based on Merchandize Trade (%GDP) and Annual CO_2 Emissions Per Capita were calculated. The top CO_2 emitting countries are Australia (15.925), Canada (16.781), and the United States (19.781) in Table 2. The three least emitters by descending order are Spain (5.977), France (6.998), and Italy (7.011). Germany (49.298), Canada (50.022), and South Korea (57.670) are the top 3 countries in merchandise trade. Australia (29.829), Japan (20.956), and the United States (16.903) are the bottom 3 in the merchandise trade. It was particularly evident for Germany and France, the results indicated, that greater trade intensity did not necessarily lead to increased emissions. Insights into these patterns might came from a focused investigation of the types of goods that were traded, energy efficiency efforts, and the role of renewable energy in trade-driven economies.

Table 2: Top and Bottom 3 Countries for each Variables

Annual CO_2 Emission Per Capita						Merchandising Trade (% GDP)					
Top 3			Bottom 3			Top 3			Bottom 3		
Country	CO_2 Emission	Trade	Country	CO_2 Emission	Trade	Country	CO_2 Emission	Trade	Country	CO_2 Emission	Trade
US	19.781	16.903	Spain	5.977	34.124	South Korea	7.521	57.670	US	19.781	16.903
Canada	16.781	50.022	France	6.998	38.653	Canada	16.781	50.022	Japan	8.966	20.956
Australia	15.925	29.829	Italy	7.011	37.72	Australia	11.704	49.298	Australia	15.925	29.829

Stacked Bar Chart Analysis

Figure 1 presents a comparison of trade and emissions per capita for each country using a stacked bar chart. The mean values for both variables were calculated. Emission means per capita ranged from 5.977 (Spain) to 19.781 (US). Mean merchandise trade (as percentage of GDP) has a range 16.903 (United States), 57.670 (South Korea). The United States shows the highest emissions and lowest trade overall intensity, while South Korea retains the highest trade percent and moderate emissions on the chart. Beyond trade volume alone, these differences imply that policy and trade arrangements have a substantial impact on emission levels (Kang & Gapay, 2023).

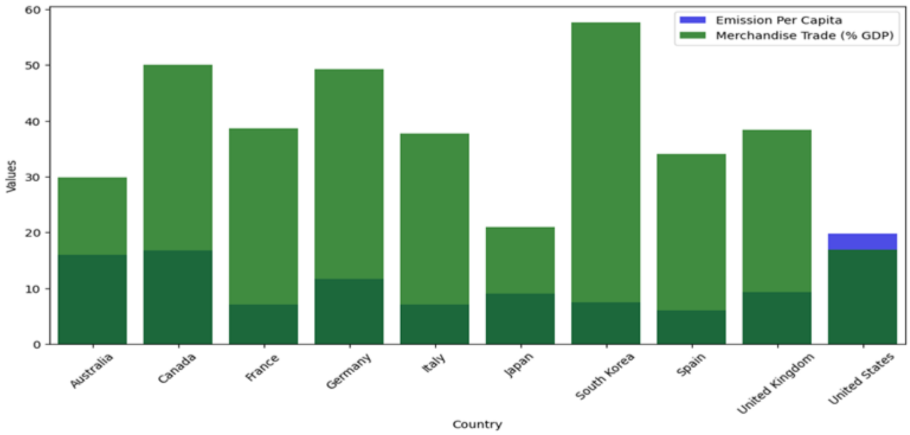


Figure 1: Emission Per Capita and Trade by Country

Time Series Analysis of Merchandise Trade

From 1970 to 2020, a time-series analysis of merchandise trade as a percentage of GDP showed different patterns in each nation. From Figure 2 we can see that the country that was growing the fastest was South Korea and reached its peak in the early 2010s. Germany and Canada maintained steady growth, particularly after 1990, which was a testament to the global integration. France and Japan

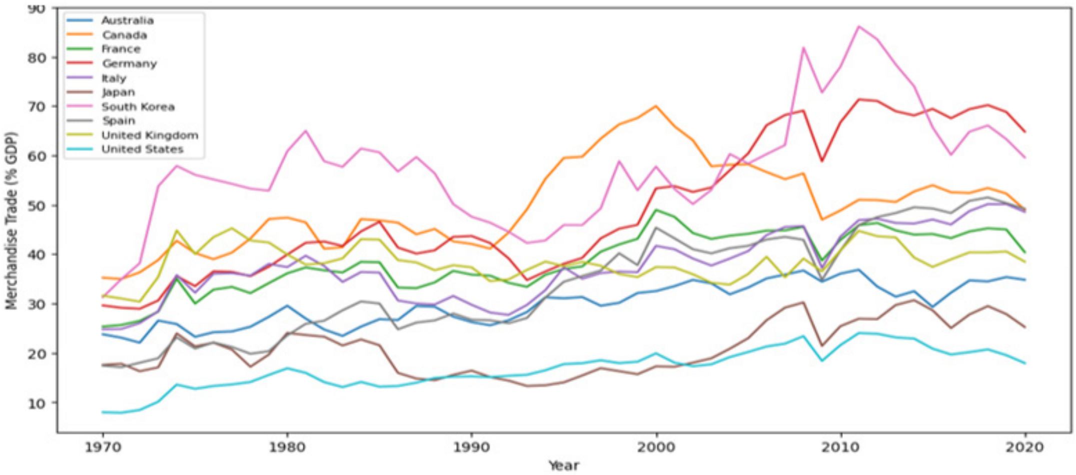


Figure 2: Merchandising Trade Over Time

have steady paths with occasional oscillations. In the US, growth was modest, including sharp declines in the 1980s and in the 2000s. Spain-UK trade activity slowly picked up. These trends suggest that trade expansion has been influenced by economic policies, industrial developments, and external market conditions.

OLS Regression Analysis

An OLS model was constructed with annual CO_2 emissions being the dependent variable and trade and population being the independent variables. The regression indicated an R-squared of 0.915, Adjusted R-squared of 0.915, and an F-statistic of 2733 with a corresponding p-value of 2.9e-272 (resulting in significant statistical power within the model), suggesting that trade and population were able to explain 91.5% of the variation in CO_2 emissions (p value < 0.01), thus demonstrating that they are engaged in a strong predictive relationship.

K-Means Clustering

A K-means clustering analysis identified three separate clusters based on trade intensity and level of emissions. Source: Cluster 0 (High Trade - Moderate Emission) the mean emission and trade of Canada, Germany, and south Korea were 10.26 and 32.06 respectively. Cluster 1 (Moderate Trade - Low Emission): France, Italy, Spain and the United Kingdom; mean emission: 7.39, mean trade: 24.79. Cluster 2 (Low Trade - High Emission): Australia, Japan, and United States (mean emission: 13.48, mean trade: 16.45) The findings showed that countries with greater volumes of trade were more likely to have moderate emissions levels while countries with smaller flows of trade were more likely to have high emission levels. This showed the role of trade efficiency, adoption of renewables, and industrial processes in shaping emission dynamics.

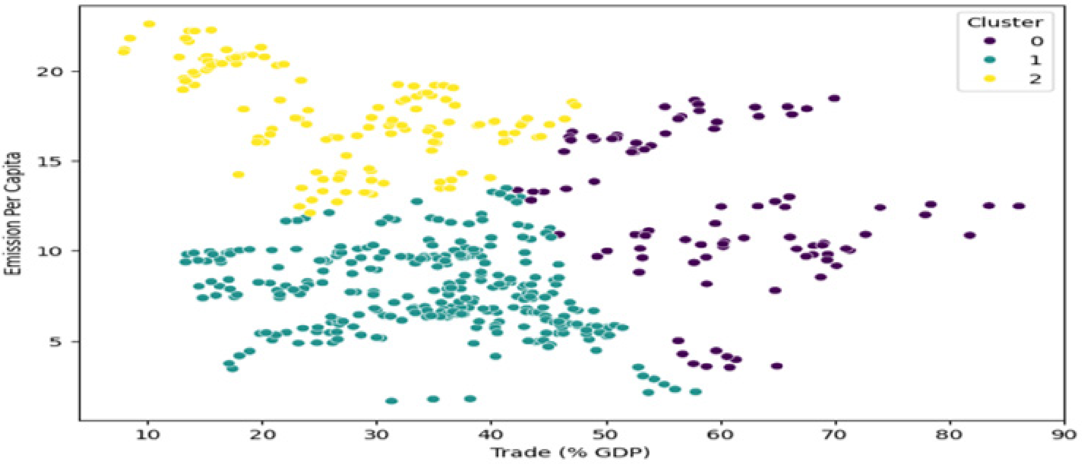
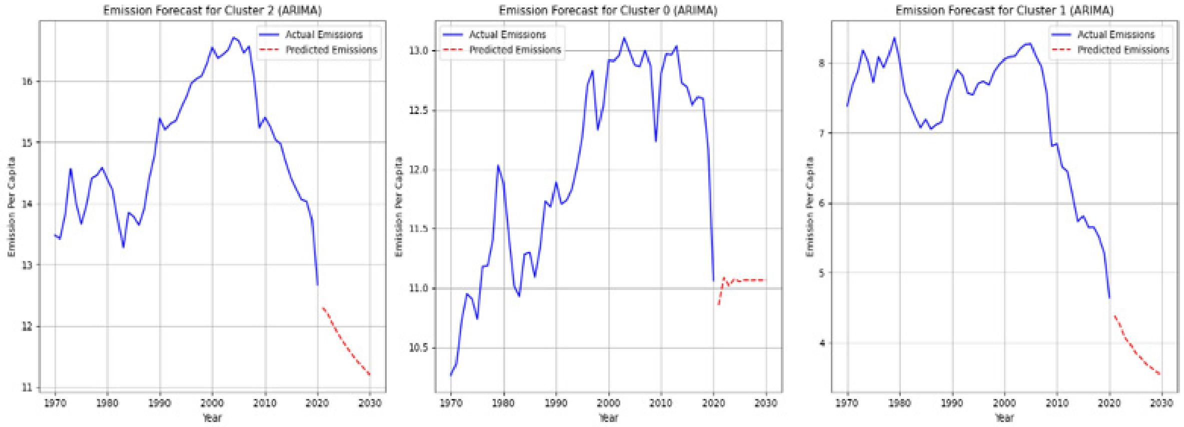


Figure 3: Clusters of Countries based on Emission and Trade

ARIMA Forecasting of CO_2 Emission

Emission Forecasting by Clusters

For each of these three clusters, the ARIMA model showed different emission trends. In Cluster 0 (Canada, Germany, and South Korea), emissions peaked during the 1990s and continued to decline steadily, and it is estimated that by 2030 emissions would have stabilized below 11. The emissions of Cluster 1 (France, Italy, Spain, and the United Kingdom) began a gradual increase in 2000 and have subsequently begun to decline. In 2030 emissions are expected to plummet around 4. If emission path is followed in accordance with prediction, emissions in Cluster 2 (Australia, Japan, and the United States) peak near 2000 and decline afterwards to around 11 in


Emission Forecast for Cluster 2 (ARIMA)

Emission Forecast for Cluster 0 (ARIMA)

Emission Forecast for Cluster 1 (ARIMA)

Figure 4: Forecasting by Clusters

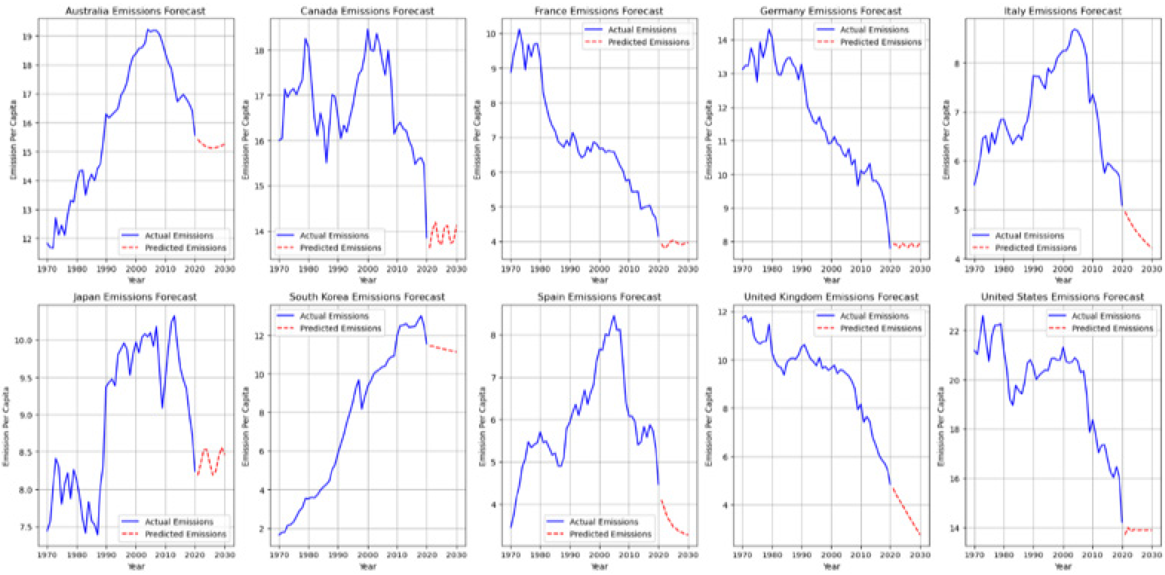


Figure 5: Emission by Country

2030. This can be seen in Figure 4. CO_2 emissions from individual nations from 2021 to 2031 provided significant insights. Given these trends that occur before the law was enacted, emissions in Australia, Italy, and Spain, as portrayed in Figure 5, are predicted to have peaked around 2000, then gradually fallen due to cleaner energy sources, implementation of environmental regulations, and improvements in industrial efficiency. In contrast, the United Kingdom has consistently decreased emissions since 1970, partly as a result of having instituted strict environmental legislation much earlier in its economic development. Under projected trends, emissions are projected to keep falling through 2030 for all countries, reflecting the impacts of international climate accords, technical advances and government-backed efforts to cut carbon emissions (W.-T. Pan *et al.,* 2024; Rahko & Alola, 2024).

Linear Regression Analysis

Using a linear regression model, the relationship between trade and emissions per capita was quantified according to the equation y=0.6207x+44.19; The r squared was 0.0445. Such poor explanatory power suggests that trade matters for emissions, but industrial policy, the means of energy, and technical advance matter more, which is shown in Figure 6. In order to improve model accuracy and offer deeper understanding into trade-emission dynamics, this emphasizes the necessity for more research that considers factors like industrial efficiency, the adoption of renewable energy, and regulatory frameworks.

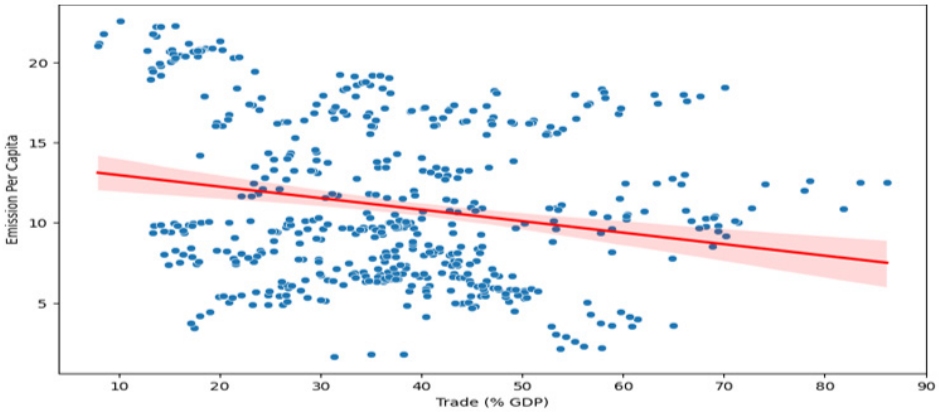


Figure 6: Regression Analysis

Discussion

The connection between carbon emissions per capita and merchandise trade as a percentage of GDP offers important information about the effects of international trade on the environment. The Pearson correlation analysis shows that trade and CO_2 emissions have distinct relationships in different nations, suggesting that trade's effect on emissions is not constant but rather varies depending on industrial activity, national economic structures, and energy policies. Strong positive correlations, for example, are seen between Canada and Australia, indicating that higher carbon emissions are linked to increased trade activity. Trade-related transportation emissions, high energy-consuming industries, and resource-intensive exports may be responsible for this (Peters & Hertwich, 2008; D.-F. Wang *et al.,* 2018). Germany and France, on the other hand, exhibit negative correlations, suggesting that rising trade has not resulted in a corresponding rise in emissions. Strong environmental laws, improved energy efficiency, and the use of cleaner production technologies could all contribute for this (G. Li *et al.,* 2020; L. Wang *et al.,* 2020). These results are consistent with the larger debate about how industrial efficiency, energy transitions, and trade liberalization affect emissions levels in various economies. The variation in trade-emission dynamics is further supported by a comparison of mean CO_2 emissions and trade levels between clusters. Comparatively lower trade percentages are seen in nations with historically high emissions per capita, such as the US, Canada, and Australia, indicating that domestic industrial and energy consumption patterns may be major contributors to emissions. Conversely, nations with high trade intensities—like Germany and South Korea—show comparatively lower emissions, which may be a result of strict environmental regulations and sophisticated production methods. These patterns support the idea that trade efficiency, energy mix, and industrial structure—rather than just trade volume—have a major impact on emissions patterns. The time-series analysis reveals that nations have taken different paths in terms of the growth of their trade and emissions. While Canada and Germany's steady trade growth since the 1990s reflects deeper integration into the world's supply chains, South Korea's rapid trade growth in the early 2010s is consistent with its export-driven economy. Economic downturns and changes in trade policies may be to blame for the observed declines in U.S. trade during the 1980s and 2000s. These results highlight how global economic cycles, technological developments, and policy interventions shape trade-emission relationships. OLS regression analysis indicates that trade and population factors account for 91.5% of the variation in CO_2 emissions, underscoring the significance of demographic shifts and economic globalization. Urbanization, energy demand, and industrial activity are all fueled by population growth, which raises emissions (Zeng *et al.,* 2022; Zhao *et al.,* 2022). According to projections from the ARIMA model, emissions in the majority of developed nations are expected to decrease by 2030, in line with worldwide efforts to reduce carbon emissions (Benveniste *et al.,* 2018). The results of simple linear regression analysis show a weak negative correlation ($R^2 = 0.0445$) between trade and emissions, indicating that trade is not the only factor influencing emissions. Other important factors include industrial policies, regulations, and energy sources.

Limitation

Despite its insights, this study has several limitations. First, because the analysis is based on historical data, it might not effectively account for upcoming changes in policy, advances in technology, or disruptions in the economy. Second, by concentrating mostly on aggregate trade and emissions data, the study may miss sector-specific differences that could offer a more complex picture of trade-related emissions. Lastly, the model did not explicitly account for external factors that could impact future trade-emission dynamics, such as economic crises, geopolitical events, and climate policies. These elements should be considered in future studies for a more thorough examination.

CONCLUSIONS

This study emphasizes the complex relationship between carbon emissions, population growth, and trade. Economic structures, energy policies, and industrial efficiency all influence the impact of trade expansion, even though it can increase emissions. The results highlight the possibility that there is not a single solution for reducing emissions. Rather, the policymakers ought to implement customized approaches that take into account regional energy transitions, demographic shifts, and trade compositions. Improving supply chain sustainability, encouraging the use of renewable energy, and strengthening environmental regulations are essential measures for cutting emissions while sustaining economic growth. Furthermore, developed economies that show a decline in emissions imply that strict regulations and breakthroughs in technology are essential to sustainability initiatives. To improve strategies for sustainable development, future studies should examine the effectiveness of policies, trade-emission interactions specific to a given sector, and new economic developments.

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