The EKC and Emissions Embodied in Trade: A Panel ARDL Approach

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Abstract

This paper investigates the Environmental Kuznets Curve (EKC) hypothesis in the context of net emissions embodied in trade for 53 developed and developing countries over the period 1995 to 2018. The central hypothesis posits that as countries become more economically developed, their environmental regulations tend to become more stringent, leading to cleaner production processes and, consequently, cleaner export baskets. This structural shift implies that net emissions embodied in trade should exhibit an inverted U-shaped relationship with income—mirroring the traditional EKC observed for domestic emissions.

Using a panel ARDL framework, the study empirically tests this hypothesis while controlling for key structural and institutional factors, including trade openness, technological innovation (proxied by R&D expenditure and patent registrations), income group dummies, carbon intensity, and population density. The results confirm the presence of a long-run cointegration relationship and reveal that net trade-related emissions initially increase with per capita income but eventually decline after a certain threshold, consistent with the EKC theory. Additional findings highlight the significant role of innovation and openness in reducing the carbon footprint of trade. These results underscore the importance of economic structure, technological development, and regulatory capacity in shaping the environmental consequences of globalization.

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Chapter 1: Introduction and Conceptual Framework

1.1 Background and Motivation

In recent decades, growing global concern over climate change has led to intense scrutiny of the environmental consequences of international trade. While economic globalization has significantly contributed to income growth and structural transformation across countries, it has also exacerbated environmental challenges—particularly those related to carbon emissions. Traditional environmental assessments often focus on territorial emissions—that is, the carbon dioxide (CO_2) emitted within a country's borders. However, this approach overlooks a crucial aspect of globalization: the emissions embodied in trade (EET), which reflect the carbon content of goods and services that are produced in one country and consumed in another.

In this context, the Environmental Kuznets Curve (EKC) hypothesis provides a useful framework for analyzing the relationship between economic growth and environmental degradation. Originally developed to explain income inequality (Kuznets, 1955) and later extended to environmental issues (Grossman and Krueger, 1995), the EKC suggests that pollution levels initially rise with income but decline after reaching a certain threshold, forming an inverted U-shaped curve. This transition is attributed to changes in production structure, stricter environmental regulations, and greater adoption of clean technologies at higher income levels.

This dissertation investigates whether a similar EKC relationship holds in the domain of net emissions embodied in trade. As countries develop, they may tighten environmental regulations, shift to cleaner domestic production, and increase imports of emission-intensive goods. Such structural shifts imply that the emissions embedded in trade may also follow an inverted U-pattern, where trade-related emissions rise with economic growth but eventually decline—particularly if cleaner technologies and regulatory mechanisms dominate trade structures at higher income levels.

1.2 Research Problem

Despite growing literature on the EKC for domestic emissions, limited attention has been paid to the emissions embedded in global trade flows. With increasing evidence of carbon leakage—where developed countries offshore pollution-intensive production to developing economies—it is crucial to understand how net EET (exports minus imports of embodied emissions) evolves with economic development. This study fills that gap by empirically testing the EKC hypothesis in the context of net emissions embodied in trade for 53 developed and developing countries over the period 1995–2018. It further explores how structural factors such as trade openness, technological innovation, carbon intensity, and population density influence the shape and turning point of this relationship.

1.3 Research Questions

This dissertation addresses the following core questions:

1. Does a non-linear (inverted U-shaped) Environmental Kuznets Curve exist for net emissions embodied in trade?

2. How do trade openness, R&D expenditure, and environmental innovation (patents) affect emissions embodied in trade?

3. Are there systematic differences in EET patterns between developed (OECD) and developing (non-OECD) countries?

1.4 Hypothesis

Grounded in the Environmental Kuznets Curve (EKC) framework, this study posits that "*net emissions embodied in trade follow a non-linear, inverted U-shaped relationship with income*". At lower income levels, countries tend to experience rising trade-related emissions driven by increased industrial activity and relatively weak environmental oversight. However, as income rises beyond a certain threshold, these emissions are expected to decline due to shifts toward cleaner production processes, adoption of environmentally friendly technologies, and the implementation of stricter regulatory frameworks. This turning point reflects a structural transformation in both domestic production and trade patterns as economies mature.

1.5 Methodological Overview

To test this hypothesis, the study uses a panel ARDL (Autoregressive Distributed Lag) model, which allows for distinguishing between short-run and long-run dynamics. The dependent variable is net EET, constructed using data from the OECD's Inter-Country Input-Output (ICIO) TECO2 database. Independent variables include GDP per capita, its square, trade openness, environmental patent registrations, R&D expenditure, population density, and carbon intensity. The panel covers 53 countries from 1995 to 2018.

1.6 Structure of the Dissertation

The remainder of the dissertation is organized as follows::

- Chapter 2 describes the data, variables, ARDL model specification, and testing sequence.
- Chapter 3 analyzes trends in EET and visually explores the EKC.
- Chapter 4 presents the estimation results and interprets model outcomes.
- Chapter 5 offers conclusions and policy recommendations based on the findings.

1.7 Literature review

The Environmental Kuznets Curve (EKC) hypothesis suggests a non-linear, typically inverted U-shaped relationship between environmental degradation and economic growth. Initially proposed in the context of income inequality by Kuznets (1955), the environmental variant gained traction through the seminal work of Grossman and Krueger (1991), who found empirical support for the inverted-U pattern in urban air pollutants—specifically sulfur dioxide and particulate matter—across 42 countries. Their analysis, which also served as a foundation for environmental concerns during the NAFTA negotiations, concluded that economic growth initially worsens environmental quality but eventually leads to improvements after a certain income threshold is crossed Grossman & Krueger, 1991.

However, as globalization intensified and international trade became a dominant feature of modern economies, scholars began to challenge the EKC's foundational assumption of nationally bounded production and emissions. A key critique emerged from consumption-based accounting (CBA), which reallocates emissions from the site of production to the site of final consumption. This framework captures emissions embedded in imports and provides a more holistic picture of environmental burdens attributable to economic activity.

Jiang et al. (2019) offer a pertinent example of this shift in perspective. Reexamining the EKC for carbon dioxide (CO_2) emissions while accounting for international trade, their findings suggest that trade can significantly postpone the global peak in emissions. The study attributes this delay to the redistribution of emission-intensive industries from developed to developing economies, a process sometimes described as carbon leakage or pollution haven effect. Thus, while national emissions in high-income countries may decline, global emissions may remain constant or increase as production shifts across borders Jiang et al., 2019.

This pattern is reinforced by Khan et al. (2020), who assess the role of international trade, environmental innovation, and renewable energy use in G7 countries. Their panel data analysis demonstrates that while production-based emissions may show a declining trend with rising income, consumption-based CO_2 emissions continue to rise. This divergence, they argue, invalidates the EKC hypothesis under CBA frameworks and suggests that developed nations may effectively "export" their environmental degradation by importing carbon-intensive goods Khan et al., 2020.

Earlier critical examinations, such as Rothman (1998), laid foundational arguments for adopting consumption-based environmental indicators. Rothman posited that much of the perceived improvement in environmental performance in developed nations is a result of shifting pollution-intensive production abroad rather than genuine technological or structural improvements. Similarly, Bagliani, Bravo, and Dalmazzone (2008) employed the ecological footprint—a composite indicator of consumption-based environmental impact—and found only weak support for the EKC, further questioning its universality under consumption-based frameworks Rothman, 1998; Bagliani et al., 2008.

In a more recent contribution, Zhang et al. (2024) explore the role of environmental innovation and international trade in OECD countries, using a dynamic panel model to estimate the impacts on consumption-based carbon emissions. Their findings reaffirm that trade has a nonlinear influence on emissions, where increased trade openness initially exacerbates emissions but can lead to reductions when accompanied by environmental technologies and stronger regulatory frameworks. However, they note that without active policy intervention, trade alone is unlikely to ensure an EKC turning point in consumption-based emissions Zhang et al., 2024.

Similarly, Wang et al. (2024) conduct an extensive study across 147 countries, incorporating trade protectionism into the EKC framework. They highlight the complex role of trade policy: while liberalized trade can facilitate the adoption of cleaner technologies, it can also incentivize the offshoring of polluting industries. Their nonlinear modeling suggests that trade openness only leads to environmental improvements beyond a certain threshold of institutional quality and environmental governance Wang et al., 2024.

Beyond carbon emissions, alternative environmental indicators such as the ecological footprint have been employed to test the robustness of the EKC hypothesis. Hervieux and Darné (2016) found mixed results using both production- and consumption-based ecological footprints across countries. Their study indicates that while the EKC may hold for production-based measures in advanced economies, consumption-based footprints often continue to grow with income, implying that apparent improvements are contingent on the metric employed Hervieux & Darné, 2016.

Liddle (2018) further critiques the EKC using a cross-national database of consumption-based emissions. His results highlight the significant elasticity between trade and embodied emissions, suggesting that countries with high import ratios often underreport their environmental impact when relying solely on territorial emission data. Such distortions challenge the policy relevance of the EKC unless expanded to include trade-adjusted measures Liddle, 2018.

Additional empirical evidence from Nudrat et al. (2023) and Gawande et al. (2001) supports the need to reconceptualize the EKC hypothesis under a consumption-based theoretical framework. They find that countries exhibiting EKC-like trends under conventional metrics fail to meet similar thresholds when adjusted for trade-embedded emissions, particularly in emerging economies participating in global supply chains Nudrat et al., 2023; Gawande et al., 2001.

1.8 Data Description

The central outcome variable in this research is net emissions embodied in trade (EET), defined as the difference between the carbon emissions embedded in a country's imports and those embedded in its exports for each year and country. Formally, it is represented as:

$$\text{Net Emission(EET)}_{it} = \text{Emissions Embodied in Imports}_{it} - \text{Emissions Embodied in Exports}_{it}$$

This metric indicates whether a nation serves primarily as a net exporter or importer of emissions through international trade. A positive value signals a net exporter of emissions, meaning the country exports more carbon-intensive products than it imports, whereas a negative value denotes a net importer. Data for this variable is derived from the OECD's Inter-Country Input-Output (ICIO) $TECO_2$ database, which employs a multi-regional input–output model to quantify CO_2 embodied in trade flows.

To evaluate the Environmental Kuznets Curve (EKC) hypothesis, the study uses GDP per capita (in constant 2015 USD) as the main explanatory variable. This indicator, sourced from the World Bank's World Development Indicators (WDI), measures the inflation-adjusted economic output per person and is widely recognized as a proxy for economic development. It includes gross value added by resident producers plus product taxes, minus subsidies, converted to USD using 2015 exchange rates or suitable alternatives where necessary. The measure follows the 2008 System of National Accounts (SNA 2008) and is harmonized across countries through rescaling to maintain cross-national consistency. Although challenges exist—such as valuing informal activity and estimating service output—GDP per capita remains the most widely used metric for gauging national income levels.

To control for additional factors that may shape the income-emissions relationship, the model incorporates several variables rooted in economic and environmental theory. These include:

- **Environment-related patents** from the OECD as a proxy for innovation capacity, particularly for green technologies.

- **Carbon intensity**, representing CO_2 emissions per unit of GDP, capturing the ecological efficiency of production.

- **R&D expenditure** (as a share of GDP), reflecting investment in innovation by public and private institutions.

- **Population density**, which measures people per square kilometer of land, indicating demographic pressures on infrastructure and the environment.

- **Trade openness**, defined as total trade (exports plus imports) relative to GDP, illustrating the extent of global market integration.

These controls enrich the EKC analysis by addressing structural and institutional dynamics not explained by GDP alone.

In addition to these continuous variables, the study uses dummy variables for income group classifications (high-, upper-middle-, lower-middle-, and low-income), based on the World Bank's income categorization. These dummies help account for differences in governance quality, industrial composition, and environmental policies across development stages, enabling more accurate estimation of the EKC pattern.

The analysis spans 53 countries, including both OECD and non-OECD members, ensuring coverage across a wide spectrum of economic and environmental contexts. The study period from 1995 to 2018 captures an era of deepening globalization and major shifts in climate policy. The 24-year panel provides ample longitudinal variation to assess both short-term trade shifts and long-term structural transformations affecting emissions embodied in trade.

1.9 Model Framework

To investigate the Environmental Kuznets Curve (EKC) hypothesis in the context of emissions embodied in trade, this study employs a panel data regression framework with country-specific effects. The EKC posits a non-linear relationship between economic development and environmental degradation, typically expressed as an inverted U-shape (Chhabra et al., 2022; Obobisa, 2024). This is captured in the basic model, where net emissions embodied in trade are modeled as a quadratic function of GDP per capita:

$$Net\_Emission_{it}=\alpha_i+\beta_1(GDP\_PC_{it})+\beta_2(GDP\_PC_{it})^2+\varepsilon_{it}$$

Here, $Net\_Emission_{it}$ represents the net emissions embodied in trade for country i at time t, computed as the difference between emissions embodied in exports and imports. GDP_PC_{it} denotes the real GDP per capita (in constant 2015 USD), while $(GDP\_PC_{it})^2$ captures the non-linear income effect necessary to test the EKC hypothesis. The term α_i accounts for unobserved country-specific effects, and ε_{it} is the error term.

To better isolate the effect of income on emissions and account for other relevant determinants, the model is extended to include control variables all of which are recognized contributors to environmental outcomes in global panel studies (Dauda et al., 2021; Udeagha & Ngepah, 2022) and income group dummies help capture structural differences across development stages (Sharif et al., 2025). The extended model is specified as:

$$\begin{aligned}Net\_Emission_{it}=\alpha_i&+\beta_1(GDP\_PC_{it})+\beta_2(GDP\_PC_{it})^2+\beta_3PopDensity_{it}+\beta_4CI_{it}+\beta_5Patents_{it}+\\&\beta_6R\_D\_EXP\_GDP_{it}+\beta_7Openness_{it}+\gamma_1H\_dummy_i+\gamma_2UM\_dummy_i+\\&\gamma_3LM\_dummy_i+\varepsilon_{it}\end{aligned}$$

In this formulation:

- $PopDensity_{it}$ captures **population density**, reflecting demographic pressure on environmental resources.
- CI_{it} stands for **carbon intensity**, representing CO_2 emissions per unit of GDP.
- $Patents_{it}$ measures **environment-related innovation**, serving as a proxy for technological advancement.
- $R\_D\_EXP\_GDP_{it}$ denotes **gross domestic R&D expenditure** as a percentage of GDP.

- *$Openness_{it}$* is the **trade openness index**, calculated as the sum of exports and imports as a share of GDP.

To further capture structural differences across countries at varying levels of development, the model includes income group dummy variables: H_dummy_i for high-income countries, UM_dummy_i for upper-middle-income countries, and LM_dummy_i for lower-middle-income countries, with low-income countries serving as the reference category. This extended framework allows for a more comprehensive estimation of how both income and structural factors contribute to a country's net emissions embodied in trade, facilitating a robust test of the EKC hypothesis within a global panel context.

2.0 ARDL Model Framework

Given the presence of both I(0) and I(1) variables in the dataset and the aim of estimating both short-run and long-run relationships, this study adopts the Panel Autoregressive Distributed Lag (ARDL) model (Usman et al., 2022; Karedla et al., 2021). The ARDL framework is particularly suited for panel data with mixed levels of integration and is robust in small sample settings with moderate time periods, making it appropriate for the current panel of 53 countries over 1995–2018.

The general form of the Panel ARDL(p, q) model used in this study is specified as:

$$\Delta Y_{it}=\phi_i(Y_{it-1}-\theta_1 X_{1,it-1}-\theta_2 X_{2,it-1}-\cdots-\theta_k X_{k,it-1})+\sum_{j=1}^{p-1}\lambda_{ij}\Delta Y_{it-j}+\sum_{m=1}^{p-1}\delta_{im}\Delta X_{m,it-m}+\varepsilon_{it}$$

In this specification, Y_{it} represents the dependent variable, namely net emissions embodied in trade for country i at time t, while $X_{k,it}$ it denotes the explanatory variables including GDP, GDP squared, trade openness, patents, R&D expenditure, carbon intensity, population density, and income group dummies. The term ϕ_i is the error correction coefficient, which should be negative and statistically significant if a long-run relationship exists. The coefficients θ_k represent the long-run equilibrium effects of the independent variables, while λ_{ij} and δ_{im}capture short-run dynamics in the dependent and independent variables respectively. The first-differenced terms are denoted by Δ, and ε_{it} is the error term. This structure separates the short-run adjustment dynamics from the long-run equilibrium relationship, allowing for a comprehensive analysis of how changes in income and other structural variables affect trade-related emissions over time.

Estimation is performed using the Pooled Mean Group (PMG) estimator developed by Pesaran et al. (1999), Shin, and Smith (1999), which assumes long-run homogeneity of coefficients across countries but allows for heterogeneity in short-run dynamics and error variances. The PMG estimator is particularly appropriate for macro-panel data where long-run relationships are assumed to be similar across economies, but short-run adjustments differ due to country-specific policy responses and institutional differences (Chhabra et al., 2022; Obobisa, 2024). The next chapter implements this model, following unit root and cointegration tests, to assess the EKC hypothesis and the role of control variables in explaining emissions embodied in trade.

2.1 The sequencing of tests performed

At first, a graphical analysis of trends in emissions embodied in trade (EET) was conducted for all countries, including net, import, and export emissions, to observe temporal patterns and identify structural shifts. Next, the Environmental Kuznets Curve (EKC) hypothesis was graphically examined by plotting GDP per capita against EET across countries and years for net, import, and export emissions separately. Following this, a table of summary statistics was prepared to understand the central tendency, dispersion, and distributional characteristics of all variables.

Subsequently, a series of diagnostic tests were undertaken. Breusch-Godfrey LM tests were applied to detect serial correlation of order up to one, and the Durbin-Watson statistic was used to further check for first-order autocorrelation in the residuals. To identify any potential multicollinearity among regressors, the Variance Inflation Factor (VIF) test was performed. For testing heteroskedasticity, the Breusch-Pagan test was used, while Jarque-Bera (J-B) test was employed to check the normality of residuals.

After the diagnostic checks, the next step involved determining the order of integration of each variable by conducting unit root tests. The tests applied included the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test to ensure robustness of results. Once it was confirmed that the variables were integrated of order I(0) or I(1), but not I(2), the bounds testing approach to cointegration was adopted to examine the presence of long-run relationships among the variables.

Finally, based on the outcomes of the integration and cointegration tests, a panel ARDL model was estimated, appropriate for mixed levels of integration, to explore both the short-run dynamics and long-run equilibrium relationships between net emissions embodied in trade and its economic, demographic, and structural determinants.

Chapter 2: Exploring the EKC through Trade-Related Emissions

2.1 Introduction

This chapter empirically explores the Environmental Kuznets Curve (EKC) hypothesis in the context of emissions embodied in international trade. By classifying countries according to their net emission trends and analyzing the structural shifts in their trade-related carbon profiles, this chapter offers a descriptive overview of how different economies engage with emissions as they grow. In particular, the analysis focuses on identifying long-run trends and transitional dynamics across countries and income groups. The chapter also presents non-parametric graphical evidence of the EKC using export, import, and net emissions data plotted against GDP per capita. These visual representations help illustrate the non-linear relationship between economic development and trade-related environmental degradation before moving to econometric testing in the next chapter (Jiang et al., 2019; Kang, 2021).

2.2 Global Trends in Net Emissions Embodied in Trade (1995–2018)

To assess the Environmental Kuznets Curve (EKC) in the context of trade-related emissions, this study draws upon two foundational concepts. The EKC hypothesis suggests that environmental degradation initially intensifies with economic growth but improves beyond a certain income threshold, forming an inverted U-shaped relationship (Khan et al., 2020). Complementing this, the Pollution Haven Hypothesis (PHH) posits that developed countries, facing stringent environmental regulations, tend to outsource pollution-intensive industries to countries with more relaxed standards—thus becoming net importers of emissions embodied in trade (EET), while less regulated economies act as net exporters (Frodyma et al., 2022).

Analyzing the trends in EET across 53 countries between 1995 and 2018, we classify them into four distinct groups. First, countries exhibiting a sustained negative trend in EET such as China, Mexico, and Malaysia are identified as persistent net exporters of emissions, supporting the PHH (Mo & Wang, 2022). Second, countries with a consistently positive trend including Australia, France, and the United States are labeled as persistent net importers, reflecting a structural shift toward cleaner energy and greener trade patterns (Jiang et al., 2019).

In addition to these long-term patterns, the analysis reveals transitional dynamics. Countries like Brazil, Chile, and Indonesia evolved from net exporters of EET in the 1990s to net importers by the 2010s, suggesting growing environmental consciousness, domestic policy shifts, or integration of cleaner technologies (Qayyum et al., 2021). On the other hand, countries such as Brunei Darussalam and Tunisia demonstrate a reverse trend—moving from net importers to exporters—indicating possible deregulation, industrial policy changes, or increased exposure to pollution-intensive sectors (Chen et al., 2021).

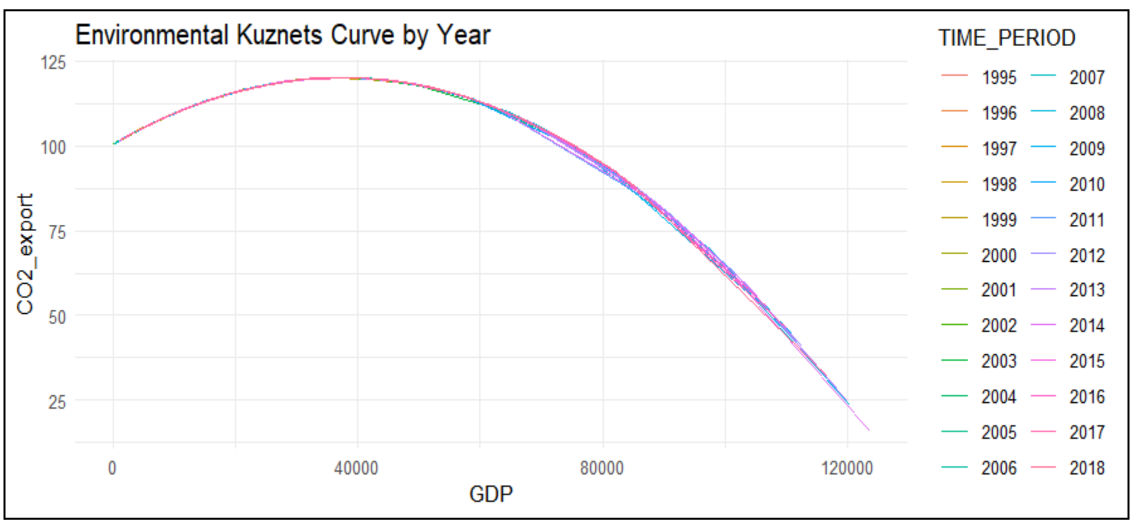
India, however, presents a unique case. Despite recording a net EET of –61 $MtCO_2$ in 1995 and a further decline to –105 $MtCO_2$ in 2018, indicating a growing role as a net exporter of emissions, its overall trend appears positive. This seeming contradiction arises from a temporary reversal between 2006 and 2010, during which India's EET turned positive, making it a net importer of emissions. Several factors explain this anomaly. First, although India was not bound by mandatory emission reductions under the Kyoto Protocol (2005) as a Non-Annex I country, it began voluntarily investing in renewable energy, energy efficiency, and clean technology adoption. Second, during this period, India experienced a surge in capital inflows and high-growth trade cycles, leading to greater importation of intermediate and capital goods with higher embodied emissions. Third, trade diversion to China, which had become the global hub for pollution-intensive manufacturing post its WTO accession in 2001, temporarily reduced India’s emissions burden. Additionally, India's service sector expansion—less emission-intensive relative to manufacturing—contributed to this transient clean trade pattern. However, the long-term resumption of emission-exporting trends reflects India's reintegration into global manufacturing value chains (Kang, 2021).

In addition to the cross-country classifications, we examine the average trend in emissions embodied in trade (EET) across OECD and Non-OECD groups. The results reveal a stark divergence: while OECD countries exhibit a positive average trend (0.636), indicating a shift toward net importers of emissions and cleaner production structures, Non-OECD countries show a negative average trend (–0.470), suggesting a continued role as net exporters of emissions. This pattern supports the Pollution Haven Hypothesis, as emission-intensive activities appear to be increasingly offshored to developing economies (Frodyma et al., 2022). Major OECD economies such as the United States, United Kingdom, Germany, France, Japan, and Australia show rising

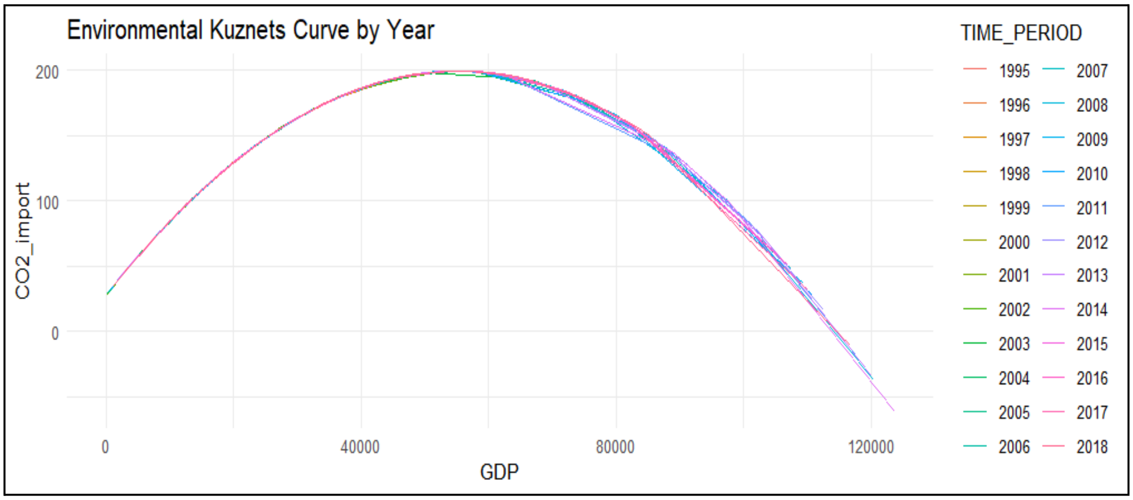
EET trends, consistent with their role in outsourcing carbon-intensive production. In contrast, key Non-OECD countries like China, India, Vietnam, Malaysia, and Kazakhstan display declining or persistently negative EET trends, implying that these economies continue to bear a larger share of the emissions burden associated with global trade (Qayyum et al., 2021; Khan et al., 2020). This divergence highlights structural inequalities in global emission responsibilities and underscores the need for differentiated policy frameworks that reflect countries' positions in international value chains.

2.3 Graphical Representation of the Environmental Kuznets Curve

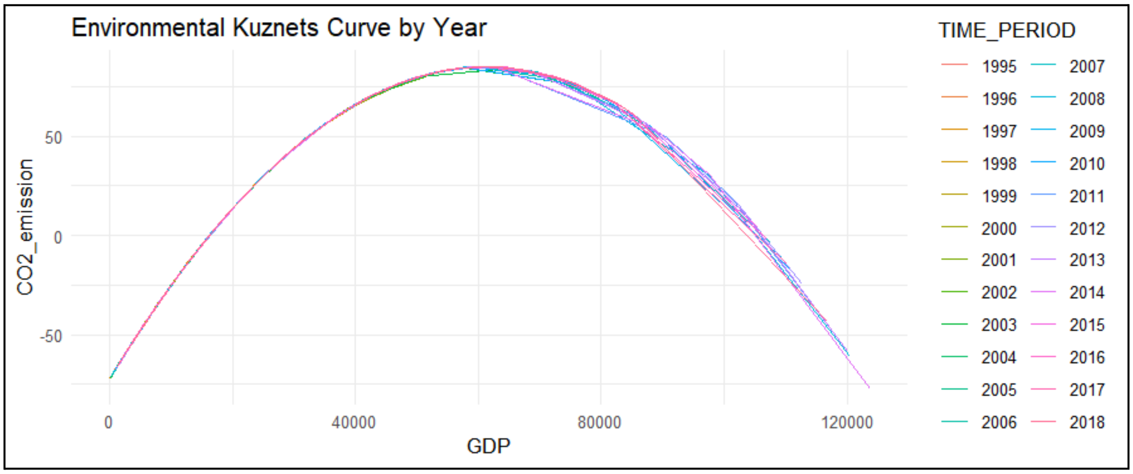
To visually examine the Environmental Kuznets Curve (EKC) hypothesis in the context of trade-related emissions, this section presents a non-parametric graphical analysis of GDP per capita against carbon emissions embodied in trade across 53 countries from 1995 to 2018. The EKC is plotted separately for emissions embodied in exports, imports, and net trade, allowing for a nuanced understanding of how the environmental impact of trade evolves with economic development (Jiang et al., 2019).



In the first panel, the EKC is plotted for emissions embodied in exports. The curve demonstrates a distinct inverted U-shape, with emissions initially rising as GDP per capita increases, reaching a peak around middle-income levels, and then gradually declining at higher income levels. Notably, the export curve starts above a value of 100, indicating that many countries—particularly low- and middle-income economies—begin their growth trajectories with a high reliance on emission-intensive export production. This reflects the role of developing countries as global suppliers of carbon-intensive manufactured goods, often due to their comparative advantage in energy- and labor-intensive industries (Mo & Wang, 2022).



The second panel displays the EKC relationship for emissions embodied in imports. This curve also follows an inverted U-shaped trajectory, starting from a value slightly above zero and rising with income before eventually tapering off. The lower starting point suggests that low-income countries import fewer goods with high embodied emissions, likely due to limited purchasing power and less integration into global consumption markets. However, as income rises, countries increase their consumption of imported goods including intermediate and final products with high carbon footprints leading to a substantial rise in imported emissions, particularly in upper-middle- and high-income economies. This supports the Pollution Haven Hypothesis, which posits that wealthier nations outsource their emissions through trade by importing from less regulated economies (Frodyma et al., 2022).



The third panel presents the EKC for net emissions embodied in trade, calculated as the difference between emissions embodied in exports and imports. This curve not only follows an inverted U-shape but also starts below –50, indicating that many countries, especially in the early stages of development, are net exporters of emissions. The negative initial value reflects a trade structure dominated by the export of emission-intensive goods and limited importation of carbon-heavy products. As GDP per capita increases, this gap narrows and eventually reverses in some countries, indicating a transition from being net emitters to net importers of emissions. This trend aligns with the broader structural shift toward cleaner domestic production and increased reliance on global value chains for carbon-intensive inputs and consumption goods (Kang, 2021).

Together, the three panels provide strong visual evidence of a non-linear relationship between income and trade-related emissions. The inverted U-shape observed across exports, imports, and net emissions supports the core EKC hypothesis. Furthermore, the initial levels and comparative slopes of each curve reflect how trade roles evolve with income: from production-driven growth in low-income countries to consumption-driven externalization of emissions in high-income countries. These patterns underscore the importance of examining trade structures and emissions jointly in understanding global environmental inequality (Khan et al., 2020; Qayyum et al., 2021).

Chapter 3: Empirical Estimation of the EKC

3.1 Introduction

This chapter presents and interprets the econometric results obtained from testing the Environmental Kuznets Curve (EKC) hypothesis for net emissions embodied in trade. The analysis begins with descriptive statistics and diagnostic test outcomes, followed by the estimation results from the basic and extended models. Both short-run and long-run dynamics are evaluated using the panel ARDL approach, and the significance, direction, and magnitude of key variables are examined. Special attention is given to the role of income, trade openness, technological innovation, and carbon intensity in shaping trade-related emissions. The results are also compared across subsamples, such as OECD and non-OECD countries, to assess heterogeneity in EKC behavior.

3.2 Summary Statistics and Diagnostic Tests

Table 1 reports the summary statistics for all the variables used in the empirical analysis. The dataset comprises 1,272 observations covering 53 countries from 1995 to 2018. The dependent variable, Net Emissions Embodied in Trade (Net_Emission_01), has a mean value of –1.1 with a standard deviation of 180.7, suggesting that on average, countries are slightly net exporters of emissions, though with high variability across the sample. This dispersion mirrors results from Hotak et al. (2020), who also document wide trade-related emission disparities across economies. The minimum and maximum values range from –1,474.7 to 995.9, indicating a wide distribution between net emission importers and exporters.

The explanatory variable GDP per capita (GDP_PC) has a mean of 23,631.2 with values ranging from 375.2 to 132,679.6 consistent with findings by Kang (2021) in OECD versus non-OECD studies. Its squared form (GDP_PC_SQR) displays significant variation, as expected, given the disparity in income levels across the sample. Trade openness averages 95.8% of GDP, indicating high trade dependency in many economies similar to results from Qayyum et al. (2021), who note high exposure to global trade as a key driver of carbon transfer. Population density (mean:

386.4) and carbon intensity (CI) (mean: 0.2) exhibit large cross-country differences. Innovation-related variables such as Patents and R&D expenditure as a percentage of GDP (R_D_EXP_GDP_01) have skewed distributions, with patents ranging from 0.2 to 18,591.1, and R&D from 0.0 to 4.9%, reflecting differing levels of technological capability Jiang et al. (2022). Dummy variables representing income groups (High, Upper-Middle, and Lower-Middle income countries) are included for structural comparison, with low-income economies serving as the reference category.

Table 1: Descriptive Statistics

Statistic	N	Mean	St.Dev.	Min	Max
TIME_PERIOD	1,272	2,006.5	6.9	1,995	2,018
Net_Emission_01	1,272	-1.1	180.7	-1,474.7	995.9
GDP_PC	1,272	23,431.2	20,480.7	375.2	123,678.7
GDP_PC_SQR	1,272	968,153,680.0	1,728,722,845.0	140,757.0	15,296,421,364.0
Openness	1,272	95.8	71.7	15.6	442.6
popdensity	1,272	386.4	1,259.4	2.3	7,908.7
CI	1,272	0.2	0.1	0.1	1.0
Patents	1,272	964.3	2,768.9	0.2	18,491.1
R_D_EXP_GDP_01	1,272	1.4	1.0	0.0	4.9
H_dummy	1,272	0.6	0.5	0	1
UM_dummy	1,272	0.3	0.4	0	1
LM_dummy	1,272	0.1	0.3	0	1
trend	1,272	11.5	6.9	0	23

The results of various diagnostic tests are presented to validate the model assumptions. The Breusch-Godfrey LM test yields an LM statistic of 0.0077 with a p-value of 0.9303, indicating no evidence of serial correlation in the residuals Adebayo (2020). This is supported by the Durbin-Watson statistic, which is 1.9933 with a p-value of 0.4472—close to the ideal value of 2—suggesting the absence of first-order autocorrelation. To test for heteroskedasticity, the Breusch-Pagan test was applied to Khan et al. (2020). The test returned a test statistic of 421.81 with a highly significant p-value (< 2.2e–16), indicating the presence of heteroskedasticity in the residuals. However, this is common in macro-panel data and will be addressed by using robust standard errors in subsequent regressions.

The Jarque–Bera (JB) test was used to assess the normality of the residuals. The test statistic of 26,840 with a p-value less than 2.2e–16 strongly rejects the null hypothesis of normality. However, as Kang (2021) notes, normality is not critical in large panels when robust estimators are used. This result suggests some skewness and kurtosis in the error distribution, which may affect inference under OLS but is appropriately handled in the ARDL framework with robust standard errors. Taken together, the diagnostic tests support the reliability of the empirical model. While heteroskedasticity and non-normality are present, the absence of autocorrelation and multicollinearity ensures that the key regression assumptions required for consistent estimation are met. These results justify proceeding to unit root testing and the panel ARDL estimation strategy in the next section.

3.3 Unit Root Tests

In panel data analysis, evaluating the stationarity of the data series is a critical step before estimating long-term relationships. A time series is considered non-stationary when its statistical properties—such as the mean and variance—fluctuate over time. To assess this formally, the current study utilizes a set of widely adopted unit root tests: the Levin, Lin & Chu (LLC) test, which assumes a common unit root process, and the Im, Pesaran and Shin (IPS), ADF-Fisher, and PP-Fisher tests, which allow for heterogeneous unit root processes. These testing methods are standard in environmental panel econometrics, as noted by Halicioglu and Ketenci (2016) and Hassan et al. (2022).

All tests were implemented using an intercept-only specification and a lag length of one, with the Newey–West automatic bandwidth selection and the Bartlett kernel applied to mitigate issues of autocorrelation and heteroskedasticity—an approach consistent with Jiang et al. (2022). The null hypothesis in each case posits the presence of a unit root, implying that the series is non-stationary. The findings reveal that variables such as GDP per capita (GDP_PC), its squared term, net emissions embodied in trade, trade openness, patents, and R&D expenditure (as a percentage of GDP) are non-stationary in levels but become stationary upon first differencing, indicating that they are integrated of order one [I(1)]. For example, the LLC test yields statistics of –12.2053 for GDP_PC and –11.0676 for Net_Emission, both highly significant at the 1% level. These results align with patterns reported in Hotak et al. (2020) and Yuan et al. (2023).

Conversely, Population Density and Carbon Intensity (CI) are stationary at level, suggesting they are I(0). Specifically, the LLC test statistics are –8.65895 for Popdensity and –3.28796 for CI, both with p-values below 0.01 under the intercept-only condition. Importantly, none of the variables in the dataset are integrated of order two [I(2)], a condition that must be avoided when applying the ARDL modeling approach (Khan et al., 2020; Adebayo, 2020). Table 2 summarizes the p-values for all unit root tests. Based on the results, the highest order of integration observed is one, thereby confirming the appropriateness of the Panel ARDL framework, which is suitable for handling variables that are either I(0) or I(1), but not I(2).

3.4 Interpretation of ARDL Estimation Results

The results from the ARDL estimation Table 3 confirm the presence of an inverted U-shaped relationship between economic development and emissions embodied in trade, consistent with the Environmental Kuznets Curve (EKC) hypothesis. Specifically, the coefficient of GDP per capita (GDP_PC) is positive and statistically significant ($\beta = 7.0254e\text{-}03$, $p < 0.001$), while the coefficient of GDP_PC squared is negative and highly significant ($\beta = –5.4426e\text{-}08$, $p < 0.001$). This pattern demonstrates that as income initially rises, net emissions increase, but after reaching a certain income threshold, further growth leads to a decline in emissions (Hotak et al., 2020; Kang, 2021).

In terms of other variables, trade openness shows a positive and significant effect on emissions in both the short and long run. The level coefficient ($\beta = 2.9265e\text{-}02$, $p < 0.001$) and the first lag are statistically significant, indicating that greater integration into global trade networks tends to raise emissions embodied in trade likely due to increased production and transportation of goods (Hassan et al., 2022). Population density also has a significant positive effect (β = 2.3891e-03, $p < 0.001$), suggesting that more densely populated countries face greater emission burdens, potentially due to urban concentration, infrastructure stress, and industrial clustering. Carbon intensity (CI) has a negative and significant coefficient (β = –4.8710e-02, $p < 0.001$), which at first may seem counterintuitive Jiang et al. (2022). However, this likely reflects a situation where countries with lower carbon intensity—i.e., more efficient or cleaner energy use—tend to import more emission-intensive goods, reducing their net emissions in trade calculations. Environmental patents, although negative in direction (β = –1.9330e-03), are not statistically significant ($p = 0.3819$), suggesting that innovation alone does not have a direct and measurable short-term impact on reducing net trade emissions. Similarly, R&D expenditure as a percentage of GDP is also not statistically significant in the contemporaneous term, although its lagged terms do show significance, implying possible delayed effects of investment in innovation on emission outcomes (Qayyum et al., 2021; Khan et al., 2020).

Regarding income group dummies, the coefficient on High-income countries (H_dummy) is positive and significant (β = 9.1455e-01, $p = 0.0263$), indicating that high-income countries tend to have higher net emissions embodied in trade, possibly reflecting their reliance on carbon-intensive imports. In contrast, the dummy for Upper-middle-income countries (UM_dummy) is not statistically significant, while Lower-middle-income countries (LM_dummy) also show an insignificant effect (Kang, 2021). The coefficient on the trend variable is negative and highly significant (β = –8.0360e+00, $p < 0.001$), capturing an overall declining trend in net emissions over time, possibly due to global decarbonization efforts and technological advances. To ensure the robustness of the inference, the t-statistics and p-values have been corrected using White's robust standard errors, addressing issues of heteroskedasticity in the residuals. This adjustment provides more reliable significance testing and reinforces the validity of the estimated (Adebayo, 2020).

Chapter 4: Empirical Insights and Policy Relevance

4.1 Introduction

This concluding chapter consolidates the key results of the research, evaluates their relevance for both environmental and trade-related policymaking, and proposes evidence-based policy recommendations. Through an in-depth investigation of the Environmental Kuznets Curve (EKC) as it relates to emissions embodied in trade (EET), the study sheds light on the complex interactions between economic development, global trade linkages, and technological innovation in shaping the international carbon footprint. It further emphasizes the persistent disparities in emission responsibilities across income groups, underscoring the need for tailored policy responses that reflect the distinct positions and capacities of developed and developing nations.

4.2 Insights into EKC

This research examines the Environmental Kuznets Curve (EKC) hypothesis in the context of emissions embodied in trade (EET), utilizing a panel dataset comprising 53 countries over the period from 1995 to 2018. By integrating indicators related to trade, environmental outcomes, and economic development, the study enhances the traditional EKC model to better reflect the interplay between economic progress and carbon emissions associated with international trade flows (Halicioglu & Ketenci, 2016). The core analysis involves assessing how GDP per capita influences net trade-related emissions, while incorporating key control variables such as trade openness, carbon intensity, population density, innovation metrics (including patents and R&D expenditures), and categorical distinctions based on income levels.

The key empirical finding confirms the existence of an inverted U-shaped relationship between income and net trade-related emissions, validating the EKC hypothesis in this broader global context. At lower income levels, countries tend to act as net exporters of emissions, relying heavily on carbon-intensive industries for growth. As income rises, emissions embodied in trade initially increase but eventually decline, reflecting structural changes in production, adoption of cleaner technologies, and a shift toward less emission-intensive trade patterns. The analysis of country-level trends further supports this outcome. Developed economies—particularly OECD members—exhibit rising import-related emissions and declining export-related emissions, indicating a shift in the carbon burden toward less developed trading partners (Jiang et al., 2022). Conversely, many non-OECD countries continue to serve as net exporters of embodied emissions, consistent with the Pollution Haven Hypothesis Qayyum et al. (2021) and Yuan et al. (2023). Transitional dynamics observed in countries like India, Brazil, and Indonesia suggest that trade-related carbon flows evolve with domestic policy, sectoral shifts, and global market integration. The study's use of a panel ARDL framework enables the differentiation of short-run fluctuations from long-run equilibrium relationships. It also accommodates variables with mixed integration orders (I(0) and I(1)) (Khan et al., 2020). The results show that trade openness, population density, and income level have significant long-run effects on net emissions embodied in trade, while innovation variables such as R&D and patents have more delayed or marginal impacts.

Taken together, these findings offer strong evidence that global trade continues to redistribute carbon emissions unevenly across the income spectrum. While higher-income countries may appear cleaner from a territorial perspective, their consumption patterns still drive significant carbon footprints abroad. As a result, international climate frameworks must go beyond territorial emissions accounting and incorporate consumption-based and trade-adjusted metrics to reflect actual emission responsibilities.

4.3 Policy Strategy and Implications

The findings of this study carry several important policy implications for both developed and developing countries, especially in the context of global trade and climate responsibility (Adebayo, 2020).

First, the confirmation of an inverted U-shaped relationship between income and net emissions embodied in trade underscores the importance of timing and sequencing in climate policy. For low- and middle-income countries that are still on the upward slope of the EKC, policies must aim to decarbonize export sectors early, without stalling industrial growth. This requires targeted support for green technology transfer, access to climate finance, and integration of low-carbon production methods into trade-intensive sectors such as manufacturing and resource extraction. Second, the results highlight the ongoing reality of carbon leakage and pollution displacement, where high-income countries reduce domestic emissions by importing emission-intensive goods. This calls for a reassessment of international climate frameworks, which currently rely predominantly on territorial-based emission accounting. There is a pressing need to complement these systems with consumption-based or trade-adjusted metrics that accurately capture a country's global carbon footprint. This would ensure greater accountability and align mitigation incentives with actual emission generation. Third, the finding that trade openness contributes positively to net emissions embodied in trade suggests that liberal trade policies, while growth-enhancing, can exacerbate environmental inequality. Thus, trade agreements must increasingly incorporate environmental safeguards, including carbon standards, technology benchmarks, and border adjustment mechanisms such as the Carbon Border Adjustment Mechanism (CBAM) being developed by the European Union (Hotak et al., 2020; Jiang et al., 2022). These tools can help internalize environmental costs and prevent unfair advantages for pollution-intensive production. Fourth, the relatively limited impact of R&D and patenting activity in reducing net emissions in the short run indicates the need for more applied, scalable, and sector-specific innovation. Governments should prioritize investments not only in basic research but also in the deployment and diffusion of clean technologies, particularly in carbon-intensive industries like steel, cement, chemicals, and textiles.

Lastly, the observed divergence in emission trends between OECD and non-OECD countries suggests the need for differentiated climate policies under frameworks like the UNFCCC. While developed economies should take the lead in reducing consumption-based emissions and supporting mitigation globally, developing countries should be supported through capacity building, finance, and equitable carbon budgeting mechanisms. In sum, the results call for a more integrated global climate strategy—one that aligns trade policy with environmental goals, redefines carbon responsibility in a globalized economy, and empowers developing countries to leapfrog to cleaner growth trajectories (Halicioglu & Ketenci, 2016; Kang, 2021).

Appendix

Table 2

Variable	LLC t*	p-value	IPS	p-value	ADF-Fisher	p-value	PP-Fisher	p-value	Order of Integration
GDP_PC	–12.2053	0.0000	–9.48997	0.0000	271.207	0.0000	348.469	0.0000	I(1)
GDP_PC_SQR	–11.8520	0.0000	–11.3828	0.0000	317.871	0.0000	438.035	0.0000	I(1)
Net_Emission	–11.0676	0.0000	–12.7478	0.0000	357.122	0.0000	863.767	0.0000	I(1)
Openness	–17.9952	0.0000	–16.5412	0.0000	468.138	0.0000	903.080	0.0000	I(1)
Patents	–7.78916	0.0000	–13.1405	0.0000	372.224	0.0000	2087.83	0.0000	I(1)
Popdensity	–8.65895	0.0000	–3.0633	0.0011	132.275	0.0428	229.844	0.0000	I(0)
R_D_EXP_GDP	–7.30160	0.0000	–7.94871	0.0000	241.422	0.0000	466.878	0.0000	I(1)
Carbon Intensity (CI)	–3.28796	0.0006	–1.93527	0.0265	152.129	0.0000	738.197	0.0000	I(0)

Table 3
Time series regression
Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	1.4722e+02	6.7253e+01	2.1890	0.0287797	*
L(Net_Emission_01, 1)	-1.5846e-02	1.4886e-02	-1.0645	0.2873205	
GDP_PC	7.0254e-03	9.0901e-04	7.7286	2.231e-14	***
L(GDP_PC, 1)	-3.1218e-03	1.2274e-03	-2.5434	0.0110973	*
L(GDP_PC, 2)	-1.5323e-04	1.9510e-04	-0.7854	0.4323705	
GDP_PC_SQR	-5.4426e-08	7.5905e-09	-7.1703	1.281e-12	***
L(GDP_PC_SQR, 1)	2.6038e-08	9.2324e-09	2.8203	0.0048744	**
Openness	-2.9265e-01	7.2915e-02	-4.0135	6.340e-05	***
L(Openness, 1)	2.5676e-01	6.7783e-02	3.7880	0.0001591	***
L(Openness, 2)	-7.4133e-02	6.2805e-02	-1.1804	0.2380791	
popdensity	-2.3891e-03	3.4377e-03	-0.6950	0.4872088	
CI	-4.8171e+02	6.1263e+01	-7.8629	8.091e-15	***
L(CI, 1)	-2.3709e+02	3.9301e+01	-6.0326	2.126e-09	***
L(CI, 2)	-9.2527e+01	2.1868e+01	-4.2313	2.495e-05	***
Patents	1.9830e-02	3.8664e-03	5.1289	3.378e-07	***
L(Patents, 1)	3.6555e-03	1.0797e-03	3.3856	0.0007324	***
R_D_EXP_GDP_01	-5.0199e+01	6.7450e+00	-7.4425	1.839e-13	***
L(R_D_EXP_GDP_01, 1)	2.5994e+01	5.6250e+00	4.6211	4.215e-06	***
L(R_D_EXP_GDP_01, 2)	2.5015e+01	6.3874e+00	3.9163	9.480e-05	***
H_dummy	9.1455e+01	4.5104e+01	2.0277	0.0428082	*
L(H_dummy, 1)	4.6409e+01	1.8517e+01	2.5062	0.0123294	*
L(H_dummy, 2)	-5.2024e+01	1.6653e+01	-3.1239	0.0018258	**
UM_dummy	7.8606e+01	4.5404e+01	1.7313	0.0836528	.
L(UM_dummy, 1)	1.3603e+01	1.2468e+01	1.0910	0.2754777	
L(UM_dummy, 2)	-3.8935e+01	1.7309e+01	-2.2494	0.0246604	*
LM_dummy	6.2039e+01	4.7599e+01	1.3034	0.1926947	
trend	-8.0360e+00	8.7288e-01	-9.2063	< 2.2e-16	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 142.8 on 1243 degrees of freedom
Multiple R-squared: 0.3893, Adjusted R-squared: 0.3765
F-statistic: 30.48 on 26 and 1243 DF, p-value: < 2.2e-16

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