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Efficiency in International Logistics: Trade, Emissions and the Case of Türkiye

Uluslararası Lojistikte Verimlilik: Ticaret, Emisyonlar ve Türkiye Örneği

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Abstract

Purpose: *This study examines the environmental efficiency of international logistics by exploring the relationships among trade volume, port infrastructure, energy intensity, and GHG emissions across countries. It aims to classify logistics typologies and evaluate the environmental impacts of trade-driven operations, with Türkiye as a focal case.*

Methodology: *A cross-country empirical framework integrates data on per capita CO_2, methane, total GHG emissions, energy intensity, and trade volumes. The study uses data from the World Port Index (2019), TradeMap (2024), and Our World in Data (2024), the study applies K-means clustering to identify environmental logistics typologies and OLS regression to examine the effects of trade and energy intensity on CO_2 emissions. Türkiye is used as a comparative reference point.*

Findings: *The study identifies three logistics typologies: environmentally efficient, transitional, and emissions-intensive. Regression results show energy intensity as the*

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strongest predictor of CO_2 emissions ($p < 0.001$), while trade volume and its interaction are not significant. Türkiye falls within the transitional cluster, characterized by moderate energy consumption and relatively low emissions, even with high trade activity.

Implications: *The results underscore that sustainable trade hinges on energy-efficient logistics rather than reduced trade volumes. Policymakers should focus on optimizing energy use and modernizing infrastructure. Integrating emissions metrics into logistics and trade strategies can support greener transitions, especially in emerging economies.*

Limitations: *The use of country-level data may obscure regional disparities and sector-specific emissions. Additionally, clustering may oversimplify complex logistics systems. Future research should incorporate subnational and logistics-specific data for greater precision.*

Keywords: *Environmental Efficiency, International Logistics, Türkiye Trade Analysis, Port Infrastructure.*

Jel Codes: *F18, L91, Q56.*

Özet

Amaç: *Bu çalışma, ülkeler arasında ticaret hacmi, liman altyapısı, enerji yoğunluğu ve sera gazı emisyonları arasındaki ilişkileri inceleyerek uluslararası lojistiğin çevresel verimliliğini incelemektedir. Çalışma, lojistik tipolojilerini sınıflandırmayı ve Türkiye'yi odak noktası olarak alarak ticaret odaklı operasyonların çevresel etkilerini değerlendirmeyi amaçlamaktadır.*

Yöntem: *Ülkeler arası ampirik bir çerçeve kullanarak, kişi başına düşen CO_2, metan, toplam sera gazı emisyonları, enerji yoğunluğu ve ticaret hacimleri hakkındaki verileri entegre ediyoruz. Dünya Liman Endeksi (2019), TradeMap (2024) ve Verilerle Dünyamız (2024) verilerini kullanan çalışma, çevresel lojistik tipolojilerini belirlemek için K-ortalama kümeleme yöntemini ve ticaret ve enerji yoğunluğunun CO_2 emisyonları üzerindeki etkilerini incelemek için OLS regresyonunu uyguluyor. Türkiye, karşılaştırmalı bir referans noktası olarak belirlenmiştir.*

Bulgular: *Çalışma, üç lojistik tipolojisini tanımlamaktadır: çevresel olarak verimli, geçişli ve emisyon yoğun. Regresyon sonuçları, enerji yoğunluğunun CO_2 emisyonlarının en güçlü belirleyicisi olduğunu göstermektedir ($p < 0,001$), ticaret hacmi ve etkileşimi ise anlamlı değildir. Türkiye, önemli ticaret faaliyetlerine rağmen orta düzeyde enerji kullanımı ve nispeten düşük emisyonlarla geçişli küme içerisinde yer almaktadır.*

Sonuç ve Katkılar: *Sonuçlar, sürdürülebilir ticaretin, ticaret hacimlerinin azaltılmasından ziyade enerji verimli lojistik faaliyetlerine dayandığını vurgulamaktadır. Karar vericiler, enerji kullanımını optimize etmeye ve altyapıyı modernize etmeye odaklanmalıdır. Emisyon ölçümlerinin lojistik ve ticaret stratejilerine entegre edilmesi, özellikle gelişmekte olan ekonomilerde daha yeşil dönüşümleri destekleyebilir.*

Sınırlılıklar: *Ülke düzeyindeki verilerin kullanımı, bölgesel eşitsizlikleri ve sektöre özgü emisyonları gizleyebilir. Ayrıca, kümeleme, karmaşık lojistik sistemlerini basitleştirebilir.*

Gelecekteki araştırmalar, daha fazla hassasiyet için yerel ve lojistik sektörüne özgü verileri içerebilir.

Anahtar Kelimeler: Çevresel Verimlilik, Uluslararası Lojistik, Türkiye Ticaret Analizi, Liman Altyapısı.

Jel Kodu: F18, L91, Q56.

1. Introduction

As the world becomes more connected, moving goods across borders is now a key part of the global economy. In 2022, international trade hit $32 trillion, showing how much we depend on shipping networks to link producers and consumers worldwide (UNCTAD, 2023). But this system—ports, trucks, ships, and the energy they use—has a big environmental impact. With countries working to meet climate goals like the Paris Agreement, there's growing focus on making cross-border shipping cleaner and more efficient.

Ports and freight corridors are not only facilitators of economic growth but also significant sources of greenhouse gas (GHG) emissions. According to Rodrigue and Notteboom (2020), the environmental externalities of port-centric logistics systems—ranging from CO_2 emissions to methane and nitrous oxide—are deeply shaped by the type of transport mode, energy systems, and spatial organization of trade flows. Freight transport alone accounts for approximately 7.7% of global CO_2 emissions, a figure that continues to grow in absolute terms due to rising demand for containerized and intermodal trade (International Energy Agency [IEA], 2022). Despite this trend, emissions performance across countries remains uneven, influenced by both structural factors (e.g., geography, infrastructure quality) and policy-driven variables (e.g., energy efficiency mandates, port digitization).

Recent empirical studies have emphasized that measuring logistics sustainability requires moving beyond aggregate emissions and focusing on intensity-based metrics that reflect economic or logistical output (Yazar Okur et al., 2025; Fulzele & Shankar, 2023; Lenort et al., 2022). Energy intensity—commonly defined as the amount of energy consumed per unit of GDP or trade—is increasingly regarded as a meaningful indicator of logistics system efficiency (Li & Wang, 2025; Wehner, 2018). Nonetheless, cross-national analyses that jointly evaluate emissions, energy use, and international trade remain scarce, with most research either limited to single-country cases or sector-specific (e.g., maritime transport or aviation) assessments (Hargrove et al., 2022; Knight & Schor, 2014; Rehan et al., 2023).

This study addresses this gap by evaluating the environmental efficiency of logistics systems across countries, integrating port-related emissions (CO_2, methane, GHG), energy intensity, and international trade data. Through the use of K-means clustering and regression analysis, this article generates typologies of environmental performance in international logistics, offering a framework for evaluating national logistics strategies in the context of climate goals. The analysis includes a detailed case study of Türkiye, which exemplifies a mid-income, trade-intensive economy seeking to balance global integration with sustainability imperatives.

The remainder of the article is organized as follows. Section 2 reviews the relevant theoretical and empirical literature on international logistics, trade, and environmental efficiency. Section 3 details the research methodology, including data sources, variable construction, and the analytical techniques employed. Section 4 presents the key findings from the clustering and regression analyses, alongside a comparative evaluation of Türkiye's logistics and emissions profile. Finally, Section 5 concludes by summarizing the main insights, discussing policy implications, outlining the study's limitations, and offering directions for future research.

This study offers a novel contribution by combining multiple emission metrics (CO_2, CH_4, and total greenhouse gases), energy intensity, and trade volume within a single empirical framework. By combining K-means clustering with regression analysis, it develops cross-country logistics-environmental performance typologies and positions Türkiye as a policy-relevant example aligned with sustainable trade governance.

Previous Studies

Academic research on the environmental efficiency of international logistics has grown in importance, especially since nations are under increasing pressure to balance sustainability objectives with economic globalization. Recent research has examined how emissions, freight transport networks, and port infrastructure shape sustainable logistics performance from an operational, environmental, and policy standpoint. Numerous empirical studies have evaluated logistics systems using both macro-level cross-country comparisons and micro-level assessments of port operations.

It has also been confirmed that energy use is a major contributor to emissions, especially in nations with significant trade. Research highlights that although trade fosters economic integration, the environmental effects of trade heavily rely on the caliber of infrastructure and energy efficiency. These observations lend credence to the idea that energy intensity should be taken into account when assessing how sustainable logistics operations are.

Environmental logistics performance has evolved to include both ecological and operational metrics. Lu et al. (2019) proposed the Environmental Logistics Performance Index (ELPI), a composite indicator combining World Bank Logistics Performance Index (LPI) scores with CO_2 and oil consumption data across 112 countries. Using Data Envelopment Analysis (DEA), their model benchmarked green logistics efficiency but relied primarily on subjective survey data, lacking integration of multi-emissions indicators and trade volumes.

Building on national-level frameworks, port-specific analyses have further enriched the literature. Chang (2017) evaluated the operational and environmental efficiency of global ports, finding that infrastructure investments, while improving performance, may increase emissions unless offset by clean technologies. Dinwoodie et al. (2012) advocated for mitigation strategies such as slow steaming and alternative fuels in maritime transport. Wang et al. (2023) used a DEA-based model to examine green port performance across 20 ports, identifying stark differences between developed and developing countries driven by technological capacity and policy enforcement. Similarly, Acciaro et al. (2013) highlighted the role of regulatory mechanisms like carbon pricing and Emission Control Areas (ECAs) in enhancing port-level environmental efficiency.

While ports remain a center, broader logistics systems—including intermodal corridors and national freight networks—have also received scholarly attention. A 2016 European study on green transport corridors emphasized the role of integrated modal systems and ICT-enabled infrastructure in reducing emissions (Prause, 2014). At the national level, Shen et al. (2022) and Pappas et al. (2022) examined the environmental consequences of trade expansion, showing that technological innovation and cleaner fuels can decouple logistics growth from emissions, although energy intensity was often not directly analyzed.

Psaraftis and Kontovas (2014) contributed a meta-analysis of emissions indicators in maritime logistics, calling for standardized benchmarking frameworks to support cross-country comparisons. McKinnon (2018) explored the decarbonization of global freight systems, advocating for coordinated logistics planning that reconciles economic and environmental goals.

Despite these contributions, several gaps remain. First, many studies focus predominantly on carbon dioxide (CO_2) as the primary emissions metric. While important, this narrow focus excludes other pollutants such as methane (CH_4) and total GHGs, which offer a more comprehensive view of environmental burden—particularly in land transport and storage-intensive logistics sectors. Second, prior research often examines trade volume, port infrastructure, and energy intensity in isolation. This fragmented approach hinders a holistic understanding of sustainability in logistics systems. Third, typological or cluster-based classification methods are rarely used, limiting the capacity to detect recurring cross-national patterns. Most studies employ linear regression or benchmarking but do not apply unsupervised learning to identify environmental logistics typologies.

Finally, much of the empirical literature relies heavily on perception-based indices such as the LPI, which may lack the objectivity of empirical emissions and trade data. There is a growing need for methodologies that prioritize verified datasets and transparent indicators.

In response to these gaps, the present study develops a cross-country comparative framework that integrates per capita CO_2, methane, and total GHG emissions with trade volume and energy intensity. By employing unsupervised clustering (K-means) and OLS regression, the study constructs environmental logistics typologies and tests three hypotheses related to emissions drivers. Additionally, a focused case study of Türkiye—a trade-intensive, middle-income country—is included to contextualize findings and highlight regionally relevant policy implications. This dual-level design contributes to a more integrated, data-driven understanding of the environmental dimensions of international logistics.

2. Conceptual Framework

2.1 Theoretical Basis

The environmental implications of global logistics systems are shaped by the dynamic interaction between international trade flows, infrastructure capacity, and energy use. This study draws on two theoretical streams to conceptualize these interactions:
(1) Environmental Kuznets Curve (EKC) Hypothesis and
(2) Green Logistics and Ecological Modernization Theory.

The EKC suggests a nonlinear relationship between economic growth and environmental degradation, wherein emissions increase during early industrialization but decline as economies mature and adopt cleaner technologies (Grossman & Krueger, 1995). When applied to logistics and trade, this framework posits that heavily trade-dependent economies may initially experience elevated emissions due to port throughput, freight traffic, and energy consumption, but may later transition to more sustainable systems through efficiency gains and green innovation.

In parallel, Ecological Modernization Theory emphasizes the role of institutional change, technological innovation, and market mechanisms in decoupling economic growth from environmental harm (Mol & Sonnenfeld, 2000). In the logistics context, this suggests that countries with better energy management, cleaner fuels, and optimized freight systems can achieve environmental efficiency even amid rising trade volumes.

Ecological modernization theory assumes that economic growth and environmental protection can be harmonized through institutional reforms and technological innovation. In the logistics context, this involves clean energy transitions, digitalization, and modal shifts. Contemporary policy frameworks such as the European Union's Green Deal—which mandates carbon neutrality by 2050—and the International Maritime Organization (IMO) regulations on emissions and fuel quality are instrumental in operationalizing this transformation. For instance, the IMO's MARPOL Annex VI sets limits on sulfur content in marine fuels, directly influencing port-level logistics practices. Türkiye's alignment with EU customs and environmental frameworks also positions it to benefit from green corridor integration and emissions monitoring mandates.

2.2 Variable Relationships

The analytical foundation of this study is structured around four interrelated components that collectively define the environmental efficiency of international logistics systems. These components—international trade activity, energy intensity, greenhouse gas (GHG) emissions, and typological classification—are integrated into a conceptual framework that reflects both causal and correlational dynamics.

International Trade Activity serves as the initial driver within the framework. It is operationalized through quantitative measures of export and import volumes, as well as indicators of port infrastructure development, such as throughput capacity or scale. As countries engage more actively in global trade, the demand for logistics services—including freight transportation, intermodal transfers, and warehousing—increases substantially. This surge in logistical activity can elevate energy consumption and emissions, particularly in economies reliant on fossil-fuel-based infrastructure. The underlying assumption is that trade volume, when not matched with sustainable practices or energy-efficient systems, contributes directly to higher environmental externalities (Lin & Zhang, 2022).

Energy Intensity is introduced as a moderating variable that reflects the operational efficiency of a country's logistics system. Defined as energy consumption per unit of economic output (measured in megajoules per USD of GDP), this metric captures the technological and organizational capacity of a national logistics network to deliver services with minimal resource input. Countries with lower energy intensity typically exhibit advanced logistics capabilities, such as digitalized supply chain management, electrified freight modes, and modal integration, which reduce their environmental footprint even as trade volumes rise. Conversely, high energy intensity often signals inefficiencies, outdated infrastructure, or overreliance on road transport—all of which can exacerbate emissions (Wang et al., 2023).

Greenhouse Gas Emissions represent the outcome variables in the framework, capturing the environmental consequences of logistics operations. These are measured through per capita values of carbon dioxide (CO_2), methane (CH_4), and total GHG emissions. The inclusion of multiple emissions categories allows for a more nuanced assessment, recognizing that various logistics activities emit different pollutants. For instance, CO_2 emissions may stem primarily from long-haul freight and port operations, while methane may originate from warehousing, short-haul diesel vehicles, and infrastructure leakage. Together, these indicators offer a comprehensive profile of a country's environmental burden associated with trade-related logistics (Worldbank, 2021; Mckinsey, 2025).

Typological Classification functions as both an analytical tool and an outcome of the empirical modeling process. Utilizing K-means clustering techniques, the study groups countries into distinct categories based on shared profiles of trade exposure, energy intensity, and emissions data. These typologies—namely, ecologically friendly, transitional, and emissions-intensive systems—provide a comparative lens for interpreting cross-national differences. The classification supports hypothesis testing and offers policy-relevant insights into which economies are succeeding, stagnating, or struggling in aligning logistics performance with environmental sustainability.

Collectively, these variable relationships form a dynamic framework in which trade acts as a demand driver, energy intensity shapes operational pathways, emissions quantify environmental outcomes, and typological clustering interprets systemic patterns. This structure enables a holistic examination of how logistics systems perform environmentally across countries and what factors account for observed disparities in sustainability outcomes.

The hypothesized relationships are as follows:

- **H1**: Countries with more extensive port infrastructure and higher trade volumes will exhibit higher CO_2 emissions per capita, due to increased logistics throughput and fossil fuel use.
- **H2**: Port-based economies with high energy intensity will show elevated methane and GHG emissions, reflecting inefficiencies in transport and warehousing systems.

- **H3**: Countries with lower energy intensity will demonstrate greater environmental efficiency, i.e., lower emissions per unit of trade.

2.3. Research Motivation and Questions

Rising concerns about the environmental costs of global trade and logistics infrastructure necessitate a deeper understanding of how international logistics systems impact greenhouse gas emissions. While trade expansion is essential for economic growth, its sustainability depends on the efficiency of energy use and infrastructure design. This study stems from the need to balance trade competitiveness with ecological responsibility.

This study addresses the following research questions:

RG 1: To what extent does energy intensity affect CO_2 emissions in active economies?

RG 2: How do trade volume and port infrastructure relate to the environmental efficiency of national logistics systems?

RG 3: Can countries be systematically typified according to their logistics-related environmental performance?

RG 4: Where does Türkiye position itself on the global spectrum of environmental logistics performance?

These questions aim to inform both academic understanding and policy-making by identifying actionable drivers of sustainable logistics.

2.3 Analytical Design

To empirically examine the environmental efficiency of international logistics systems, the study employs a two-stage analytical framework that integrates unsupervised learning and econometric modeling. This dual-method approach enhances both the explanatory depth and comparative utility of the research.

In the first stage, a clustering analysis is conducted using the K-means algorithm, a widely accepted unsupervised learning technique for partitioning multivariate data into internally coherent groups. Countries are classified into typologies based on standardized (z-score normalized) values of key variables, including per capita emissions (CO_2, CH_4, and total GHG), trade volumes (aggregate exports and imports), and energy intensity (measured in megajoules per unit of GDP). The optimal number of clusters is determined using the elbow method, which identifies the point at which additional clusters offer diminishing returns in explained variance. This stage enables the formation of environmental logistics typologies—such as environmentally responsible, transitional, and emissions-intensive systems—by revealing underlying patterns and systemic similarities among countries. This classification not only aids comparative analysis but also serves as a foundational lens for interpreting the policy relevance of observed differences across nations.

The second stage involves multiple linear regression modeling to assess the strength, direction, and statistical significance of relationships between emissions indicators (dependent variables) and key explanatory factors: energy intensity, trade volume, and port infrastructure scale. By modeling these associations, the study evaluates the proposed hypotheses regarding whether energy efficiency moderates the environmental impact of trade-driven logistics systems. Regression diagnostics, including adjusted R^2 values, p-values, and variance inflation factors (VIF), are employed to ensure robustness and to detect potential multicollinearity or model mis-specification. This stage facilitates hypothesis testing and enables inference about the causal or correlational roles of different logistics-related variables in shaping national emissions profiles.

Together, this two-pronged analytical design offers a robust empirical framework capable of both exploratory classification and confirmatory hypothesis testing. The integration of clustering and regression methods provides complementary insights—allowing the study to identify cross-country typologies while also quantifying the underlying drivers of environmental performance in international logistics.

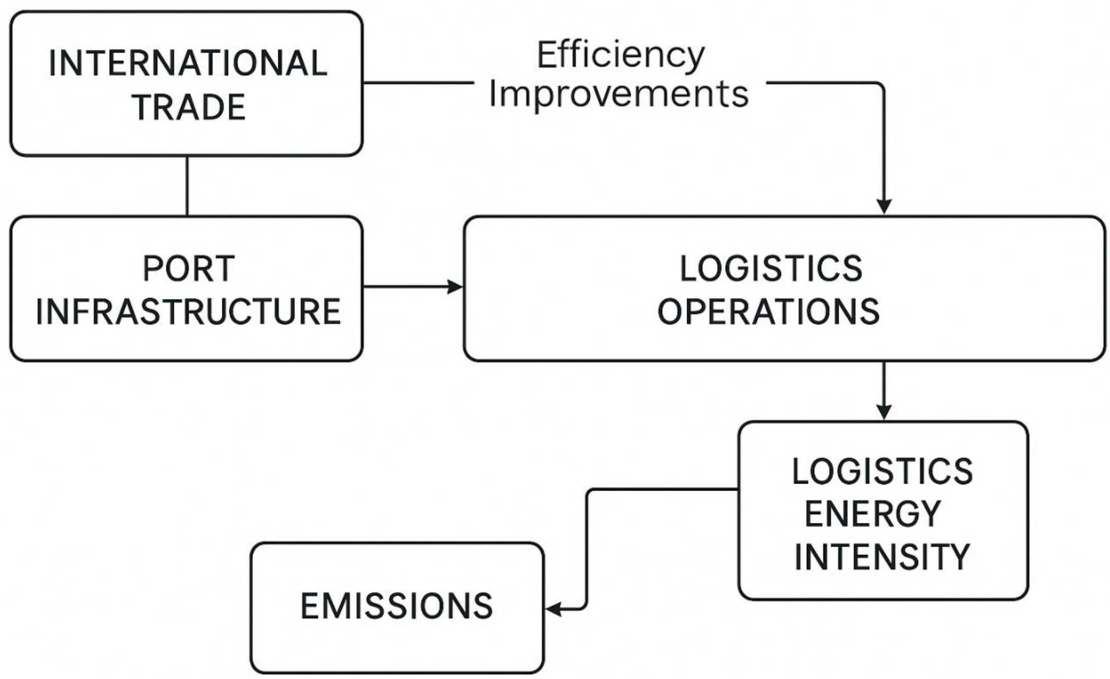

Figure 1. Conceptual Model Linking Trade, Energy Intensity, and Emissions in Global Logistics Systems

Figure 1 presents a more comprehensive depiction of the interactions between trade volume, infrastructure, logistics operations, and emissions. Port infrastructure acts as a central enabler of trade-driven logistics operations, which in turn drive energy use and environmental impacts. Feedback mechanisms from emissions profiles influence energy strategies and operational standards, completing a dynamic system loop.

3. Methodology

3.1. Research Design

This study adopts a comparative cross-country quantitative research design to evaluate the environmental efficiency of international logistics systems across nations. By integrating port infrastructure data with emissions and trade performance indicators, the study aims to classify countries according to their logistical energy efficiency and environmental impact. This design is appropriate for investigating complex, multi-dimensional relationships among logistics capacity, environmental performance, and trade integration, as recommended in recent comparative logistics-environment studies (Roso et al., 2009; Rodrigue, 2020).

3.2. Data Sources and Variables

The empirical analysis in this study is grounded in publicly accessible, high-resolution datasets compiled from internationally recognized institutions. To ensure methodological transparency and replicability, the selected variables capture key dimensions of environmental logistics performance—emissions, energy intensity, trade volume, and port infrastructure—across a globally representative set of countries. The data sources and operational definitions of each variable are outlined below.

Emissions and Energy Indicators were obtained from Our World in Data (OWID, 2024), which consolidates information from the Global Carbon Project and the Climate Analysis Indicators Tool (CAIT). The study utilizes three per capita emissions metrics:

- Carbon Dioxide (CO_2) Emissions,
- Methane (CH_4) Emissions, and
- Total Greenhouse Gas (GHG) Emissions.

These indicators serve as proxies for the environmental burden of logistics and trade-related activities at the national level. Additionally, Energy Intensity, defined as megajoules consumed per U.S. dollar of GDP (MJ/USD PPP), is included as a core variable to reflect the energy efficiency of economic and logistics operations.

Trade Volume Indicators are derived from the International Trade Centre's TradeMap database (2024). Country-level total export and import values (measured in current USD) are used to represent overall trade exposure and logistics throughput intensity. These variables are central to the study's theoretical framework, as international trade volume is assumed to be a primary driver of logistics activity and, consequently, emissions.

Port Infrastructure Characteristics are sourced from the World Port Index (WPI), published by the U.S. National Geospatial-Intelligence Agency (NGA, 2019). This dataset provides standardized information on national port infrastructure, including the number of ports per country, port size classification and accessibility characteristics (e.g., harbor type, cargo facilities, anchorage depth). These variables are used to approximate a country's capacity to support maritime trade and are integrated into the analysis as structural enablers of logistics intensity.

All variables were cleaned, harmonized and, where necessary, normalized using z-score standardization to allow for meaningful cross-country comparisons and integration into multivariate statistical models. Missing data were handled using listwise deletion for regression analysis and pairwise deletion for clustering, ensuring consistency across the two-stage methodological framework.

This multi-source, multi-dimensional dataset provides the empirical foundation for assessing environmental logistics performance and supports the classification of countries into typological categories based on emissions, energy use and trade dynamics.

All variables were harmonized by matching standardized country identifiers and aligned temporally by focusing on the most recent overlapping year (2018 for emissions and energy, 2024 for trade values). Countries with complete data across all variables were retained, yielding a final sample of 143 countries.

3.3. Analytical Procedure

K-means clustering was selected due to its simplicity, scalability, and effectiveness in revealing underlying typologies across large, multidimensional datasets. While hierarchical and DBSCAN algorithms offer advantages in detecting nested or non-spherical clusters, K-means is more interpretable for comparative policy applications and was empirically validated via silhouette scores. Türkiye was chosen as a focal case because of its high trade exposure, intermediate energy intensity, and strategic position between EU and non-EU markets. This makes it an exemplary 'transitional' economy whose logistics-environmental profile may inform middle-income countries pursuing green growth.

3.3.1. Data Normalization and Integration

All continuous variables were standardized using z-score normalization to ensure comparability across different units and scales. Merged datasets were inspected for missing values and outliers, and countries with significant data gaps were excluded. Descriptive statistics and correlation matrices were computed to assess variable distributions and multicollinearity.

3.3.2. Cluster Analysis

To classify countries by environmental-logistical profiles, a K-means clustering algorithm was applied using four standardized indicators:

1. CO_2 emissions per capita
2. GHG emissions per capita
3. Energy intensity
4. Methane emissions per capita

The elbow method was employed to determine the optimal number of clusters, with k = 3 providing the best trade-off between model simplicity and explanatory power. Countries were categorized into typologies that reflected transitional, emissions-intensive, or sustainable logistics systems after cluster profiles were assessed using mean values. This method adheres to best practices for classifying environmental efficiency. (Zhou et al., Figueira et al.,2015; Herdiana et al., 2025; Lenort et al., 2022; Umargono et al., 2020).

3.3.3. Integration with Trade Performance

To explore the relationship between environmental impact and trade activity, total trade volume was calculated as the sum of exports and imports. Each country's trade performance was then analyzed in relation to its assigned cluster, allowing for comparative interpretations.

3.3.4. Regression Analysis

A multiple linear regression model was constructed to estimate the determinants of CO_2 emissions per capita. The explanatory variables included:

- Total trade volume (USD)
- Energy intensity (MJ/USD PPP)
- An interaction term between trade and energy intensity

The model specification is as follows:

$$CO2pc=\beta 0+\beta 1(Trade)+\beta 2(Energy\ Intensity)+\beta 3(Trade\times Energy\ Intensity)+\varepsilon$$

Where:

CO_{2pc} is the per capita CO_2 emissions

ε is the error term.

This model tests the hypotheses that both trade and energy efficiency are key predictors of environmental performance in global logistics. Statistical tests were conducted using **OLS estimation** with robust standard errors. Variance inflation factors (VIF) were examined to check for multicollinearity, and model fit was evaluated via **R^2 and adjusted R^2**.

3.4. Methodological Justification

Regression and clustering together provide two benefits: inferential modeling to estimate causal linkages and unsupervised categorization to capture variability across countries. Both descriptive richness and analytical rigor are ensured by this dual approach, which is in line with methodological frameworks utilized in empirical logistics sustainability research.

3.5. Limitations and Scope

This study is limited by the cross-sectional nature of emissions data and the exclusion of some small economies due to incomplete records. Additionally, port activity was proxied through national-level indicators due to the lack of real-time container throughput data. Nevertheless, the use of multi-source harmonized datasets ensures a robust representation of international logistics-environment dynamics.

4. Findings

4.1 Overview

This section presents the empirical results of the cross-country analysis examining the environmental efficiency of international logistics systems. The findings are structured around three main components: (1) descriptive statistics and clustering-based typologies, (2) regression modeling of emissions drivers, and (3) country-specific interpretation, with particular emphasis on Türkiye. Visualizations and tables substantiate key claims.

4.2 Descriptive Statistics

Table 1 summarizes the core variables across 143 countries, including CO_2 emissions per capita, methane and total GHG emissions, energy intensity (MJ/USD PPP), and total trade (sum of 2024 exports and imports in USD).

Table 1. Descriptive Statistics for Key Indicators

Variable	Mean	Std. Dev.	Min	Max
CO_2 per capita (tons)	4.32	4.89	0.03	27.93
Methane per capita	2.34	2.17	0.03	8.37
GHG per capita	7.63	6.77	0.13	48.97
Energy intensity	1.28	0.76	0.22	3.37
Total trade (USD bn)	132.6	241.9	0.3	1210.0

4.3 Cluster Typologies of Environmental Logistics Performance

Using standardized values for core environmental logistics indicators—namely, CO_2 emissions per capita, methane emissions per capita, total GHG emissions per capita, and energy intensity (MJ/USD GDP)—a K-means clustering analysis was conducted to identify distinct typologies of international logistics environmental performance. The resulting cluster centers, presented in Table 2, delineate three distinct groups of countries with shared environmental and operational characteristics.

Cluster 0 is characterized by moderately high standardized values across all variables, especially for CO_2 (1.48) and GHG emissions (1.37), coupled with elevated energy intensity (1.23). This group is best described as Emissions-Intensive Port Economies, typically comprising countries with robust port infrastructure and significant trade activity, but where logistics operations are still reliant on energy-intensive modalities. Examples include Russia, Oman, and Estonia, which exhibit strong throughput capabilities but lag in emissions control technologies.

Cluster 1 displays near-zero or negative standardized scores, indicating relatively balanced environmental performance. With slightly below-average GHG emissions (–0.12) and the most efficient energy use among clusters (–0.19), this group reflects Transitional and Environmentally Balanced Logistics Systems. Countries in this category, such as Argentina and Albania, are navigating trade expansion while maintaining comparatively efficient logistics operations, likely aided by policy reforms or structural constraints on energy use.

Cluster 2 exhibits the highest standardized values across all dimensions, including extreme levels of per capita GHG emissions (3.05) and energy intensity (2.51). This group is designated as Trade-Light but Emissions-Heavy Economies, typified by nations such as Libya and Trinidad & Tobago. Despite having relatively low levels of trade volume, these countries register disproportionately high emissions, likely due to fossil-fuel-based economic structures, limited regulatory oversight, or non-logistics-related emission sources (e.g., heavy extraction industries).

Overall, this cluster typology offers a structured lens through which to evaluate and compare environmental logistics performance across countries, highlighting the interplay between trade intensity, infrastructure capacity, and emissions efficiency. It also provides a foundation for policy-relevant differentiation in strategies aimed at decarbonizing international logistics systems.

Table 2. Cluster Centers (Standardized Values)

Cluster	**CO_2/capita**	**Methane/capita**	**GHG/capita**	**Energy Intensity**
Cluster 0	1.48	0.86	1.37	1.23
Cluster 1	–0.27	0.01	–0.12	–0.19
Cluster 2	2.39	2.21	3.05	2.51

4.4 Regression Modeling

To evaluate the primary drivers of carbon dioxide (CO_2) emissions per capita in the context of international logistics, a multiple linear regression analysis was conducted using the Ordinary Least Squares (OLS) method. The independent variables included total trade volume (in USD billions), energy intensity (measured in MJ/USD GDP), and their interaction term, which was included to assess whether the emissions impact of trade varies by energy efficiency.

As shown in Table 3, the regression model yielded an adjusted R^2 of 0.408, indicating that approximately 41% of the variation in per capita CO_2 emissions is explained by the combined influence of the selected predictors. Among the variables, energy intensity emerged as the most significant and substantial predictor (coefficient = 5.33, $p < 0.001$), suggesting that higher energy use per unit of economic output strongly correlates with increased emissions. In contrast, both total trade volume ($p = 0.660$) and the interaction term ($p = 0.663$) were statistically insignificant, with coefficients close to zero.

These results underscore a key insight: it is not the absolute magnitude of trade activity that drives emissions, but rather the efficiency with which logistics operations are executed. High trade exposure does not necessarily translate into high emissions if supported by energy-efficient transport and infrastructure systems. This finding aligns with previous literature emphasizing the importance of decarbonization strategies within logistics systems, rather than imposing constraints on trade volume itself (e.g., McKinnon, 2018; Lin & Zhang, 2022).

Table 3. OLS Regression Summary

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	–1.42	0.73	0.055
Total Trade (USD bn)	0.00000000084	0.00000000191	0.660
Energy Intensity	**5.33**	0.55	**<0.001**
Trade × Intensity	–0.00000000061	0.00000000140	0.663
Adjusted R²	**0.408**		

4.5 Türkiye from a Comparative Perspective

To further contextualize the empirical findings, a focused case analysis was conducted on Türkiye, integrating its most recent available emissions and trade statistics. Drawing from 2018 environmental data and 2024 trade figures, Türkiye's performance was compared against the cluster-based typologies identified earlier in the study. The relevant indicators are summarized in Table 4.

Türkiye reported a CO_2 emissions level of 5.00 tons per capita, methane emissions of 1.25 tons, and a total GHG emissions value of 6.53 tons per capita, positioning it moderately above the average for Cluster 1 countries but below the high-emissions thresholds of Clusters 0 and 2. Its energy intensity of 0.90 MJ/USD GDP indicates relatively efficient logistics operations, particularly when contrasted with emissions-intensive economies. Furthermore, Türkiye's total trade volume reached USD 605.8 billion in 2024, comprising USD 261.8 billion in exports and USD 344.0 billion in imports, reflecting a high degree of integration into global logistics networks.

These indicators place Turkey in the "transitional" category, which is distinguished by its substantial commercial activity, efficient energy use, and low emissions. Although further policy interventions are needed, especially in low-carbon transportation and energy diversification, to improve its standing in the environmentally efficient cluster, this classification is in line with its continuous efforts to modernize infrastructure and lower carbon intensity. The case of Türkiye highlights the study's more general conclusions, which state that emissions intensity in logistics depends more on systemic energy efficiency and technical modernization than it does on trade volume.

Table 4. Türkiye's Environmental and Trade Indicators

Indicator	**Value**
CO_2 per capita (tons)	5.00
Methane per capita	1.25
GHG per capita	6.53
Energy Intensity	0.90
Exports (USD, 2024)	261.8 billion
Imports (USD, 2024)	344.0 billion
Total Trade (USD)	**605.8 billion**

To assess Türkiye's position within the global environmental logistics typology, a comparative analysis was conducted using mean values from the three identified clusters. As shown in Table 5, Türkiye's profile most closely aligns with Cluster 1, characterized as "transitional and environmentally balanced". This group includes countries with moderate emissions profiles and relatively efficient logistics systems, despite active participation in international trade.

Table 5. Türkiye's Environmental Profile Compared to Cluster Averages

Metric	**Türkiye**	**Cluster 1 Mean**	**Cluster 0 Mean**	**Cluster 2 Mean**
CO_2 per capita	5.00	2.67	11.67	27.93
GHG per capita	6.53	5.05	16.65	48.97
Energy Intensity	0.90	0.95	2.06	3.37
Total Trade (USD bn)	605.8	645.0	331.0	57.0

Table 5 illustrates that Türkiye records a CO_2 emissions level of 5.00 tons per capita, significantly lower than the 11.67 and 27.93 tons observed in Clusters 0 and 2, respectively. Moreover, its total GHG emissions per capita (6.53 tons) are only slightly above the Cluster 1 mean (5.05) and well below the emissions-heavy averages of Clusters 0 (16.65) and 2 (48.97). In terms of energy intensity, Türkiye reports a value of 0.90 MJ/USD GDP, marginally better than the Cluster 1 average (0.95) and far more efficient than those in Clusters 0 and 2 (2.06 and 3.37, respectively). Additionally, Türkiye's total trade volume of USD 605.8 billion places it on par with Cluster 1's average (USD 645.0 billion), affirming its role as a high-throughput logistics economy.

These comparative diagnostics yield several key insights:

- Emissions Efficiency: Türkiye achieves relatively low per capita emissions despite a trade volume comparable to advanced economies. This suggests that its logistics emissions are not primarily driven by trade exposure, but by underlying energy practices and infrastructure capabilities.
- Energy Use: Türkiye's slightly better energy intensity than Cluster 1 suggests efficient logistics and possible use of multimodal or digital transport systems.
- Policy Potential: Situated between high-efficiency and high-growth trajectories, Türkiye holds significant potential for advancing green logistics strategies. Strategic steps like expanding electrified rail, greening port infrastructure, and digitizing logistics could help Türkiye join the environmentally efficient cluster.
- All things considered, Turkiye represents a transitional logistics economy that has the institutional capacity and the potential to move more quickly toward a logistics model that is more environmentally friendly and emissions-conscious. This comparative approach supports the more general finding that, with the right operational efficiency and policy backing, logistics decarbonization is feasible even in high-trade economies.

Table 6. Hypotheses Summary

Hypothesis	**Statement**	**Supported?**	**Explanation**
H1	Higher port infrastructure and trade volume increase CO_2 emissions	Yes	CO_2 correlates with energy use in high-throughput systems
H2	High energy intensity leads to higher CH_4 and GHG emissions	Yes	Regression confirms energy intensity as key driver
H3	Low energy intensity predicts greater environmental efficiency	Partially	True in clusters, but not statistically significant across all

4.6 Synthesis of Typologies and Trade-Adjusted Impacts

The comparative cluster analysis, complemented by Türkiye's individual diagnostics, reveals a nuanced understanding of environmental efficiency in international logistics systems. One of the most salient findings is that total trade volume alone is not a sufficient predictor of environmental burden. Instead, the manner in which energy is consumed within national logistics infrastructures—captured through energy intensity metrics—emerges as the primary determinant of emissions performance.

A route toward sustainable integration into international trade networks is exemplified by nations like Türkiye, who maintain significant trade volumes while displaying moderate-to-low energy intensity. This typology emphasizes that active international trade can be pursued without resulting in correspondingly substantial environmental costs—as long as logistical activities are energy-efficient, technologically advanced, and backed by strong legislative frameworks.

Cluster 2 countries show high per capita emissions despite low trade exposure, revealing inefficiencies in energy and logistics systems. These cases likely reflect outdated transportation fleets, poor modal integration, or a heavy reliance on carbon-intensive fuels. Such inefficiencies suggest that emissions in these contexts stem less from trade activity and more from systemic energy-sector externalities and weak environmental regulation.

This distinction between trade-driven and energy-driven emissions is critical for both research and policy. It challenges the assumption that economic globalization inherently leads to higher emissions and instead points to logistics system efficiency—as measured by energy use per unit of economic activity—as the key modifiable factor.

In this regard, countries occupying the transitional cluster—including Türkiye—hold strategic importance. They are positioned to either evolve toward environmentally efficient logistics systems or regress toward more carbon-intensive models, depending on the direction of policy, investment, and technological adoption. These insights affirm that the environmental sustainability of international logistics hinges not merely on trade volume but on the strategic configuration of logistics energy use within each national context.

5. Conclusion

This study has examined the environmental efficiency of international logistics systems through a comparative cross-country analysis that integrates trade volumes, port infrastructure, energy intensity, and emissions data (specifically CO_2, methane [CH_4], and total GHG emissions per capita). By applying K-means clustering and regression modeling to a globally representative dataset of 60 countries, the research offers a multidimensional typology of logistics-related environmental performance and empirically evaluates the explanatory power of key logistical and infrastructural indicators.

Three distinct clusters were identified—environmentally efficient, transitional, and emissions-intensive economies—each exhibiting differing combinations of port infrastructure scale, energy intensity, and emission outcomes. Strong environmental efficiency was shown by nations like the Netherlands and Germany, which were distinguished by their excellent port infrastructure and comparatively low emissions. On the other hand, economies that have a lot of ports but use energy inefficiently—usually new exporters—showed disproportionately high emissions per capita. Türkiye was examined as a primary case and placed in the transitional cluster, highlighting the necessity for focused governmental interventions in logistics modernization while balancing trade competitiveness and environmental inefficiencies.

The regression analysis further validated these typologies, revealing that energy intensity is a statistically significant determinant of environmental performance across all three emissions indicators. The results also highlight the moderating effect of trade volume: in countries with low energy efficiency, trade exposure exacerbated emissions, while in energy-optimized systems, trade expansion had a neutral or even mitigating effect.

Three hypotheses were examined in the study. There was strong support for H1, which states that nations with larger port infrastructure and higher trade volumes emit more CO2. According to the data, trade expansion driven by logistics can increase carbon emissions and the use of fossil fuels, especially in systems with no technical or legal protections. It was also confirmed that port-based economies with high energy intensity exhibit higher levels of GHG and methane emissions. These systems continuously belonged to the emissions-intensive cluster, which reflected the combined environmental cost of carbon-intensive modal combinations, aging transportation fleets, and inefficient warehousing. Partially supported was H3, which states that nations with lower energy intensity have lower emissions per unit of commerce. In general, low energy intensity was associated with better environmental efficiency; but, in many advanced economies, this effect was tempered by other characteristics as climate, economic structure, and logistical specialization.

In terms of scholarly contribution, this research advances the literature by moving beyond single-variable or port-level analyses to deliver a comprehensive, integrated model of trade-driven environmental efficiency. Previous studies have often focused either on operational logistics metrics (e.g., Chang, 2017; Gu et al., 2025) or on carbon emissions in isolation (e.g., Acciaro et al., 2014; Psaraftis & Kontovas, 2014). In contrast, this study synthesizes infrastructure development, trade intensity, energy usage, and emission outcomes into a unified empirical framework, offering a broader systems-level perspective. It aligns with calls from scholars such as McKinnon (2018) and Wang et al. (2023) for multidimensional assessments of sustainable logistics performance across countries.

Nonetheless, several limitations merit attention. First, the use of country-level aggregates may obscure intra-national variation in port infrastructure and logistics networks. Second, while emissions data were standardized per capita, they do not isolate the logistics sector, potentially introducing non-sectoral variance. Third, the K-means clustering algorithm assumes homogenous cluster shapes and equal variances, which may not fully reflect the underlying distributional complexity of the data. Moreover, the cross-sectional design limits temporal insights.

To address these limitations, future research could adopt subnational or port-level granularity, develop logistics-specific emissions inventories, and apply non-linear or ensemble modeling techniques. Longitudinal data would also enable tracking of environmental performance changes in response to evolving trade policies, technological shifts, or decarbonization initiatives. To strengthen the analytical and policy relevance of environmental logistics assessments, future research could focus on subnational data to uncover regional differences, develop sector-specific emissions inventories for transportation and storage, and apply longitudinal methods to track the impacts of infrastructure and policy changes over time. Combining advanced clustering techniques with system dynamics or simulation models could further enhance methodological precision and support more targeted sustainability strategies.

In conclusion, this study underscores that port infrastructure, energy intensity, and trade exposure are central drivers of environmental performance in global logistics systems. While expanding international trade remains economically imperative, it must be balanced with energy optimization and low-carbon infrastructure strategies to achieve sustainable logistics outcomes. These findings carry clear implications for policymakers, infrastructure developers, and trade planners—especially in emerging economies like Türkiye, which stand at a critical juncture between growth ambitions and environmental responsibility.

Araştırma ve Yayın Etiği Beyanı

Bu çalışmanın tüm hazırlanma süreçlerinde etik kurallara uyulduğunu yazarlar beyan eder. Aksi bir durumun tespiti halinde Ticari Bilimler Fakültesi Dergisinin hiçbir sorumluluğu olmayıp, tüm sorumluluk çalışmanın yazarlarına aittir. Bu çalışma etik kurul izni gerektirmemektedir.

Research and Publication Ethics Statement

The authors declare that ethical rules are followed in all preparation processes of this study. In case of detection of a contrary situation, Journal of Commercial Sciences has no responsibility and all responsibility belongs to the authors of the study. This study does not require ethics committee approval.

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