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Research

Carbon emissions across income groups: exploring the role of trade, energy use, and economic growth

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Abstract
This study investigates the interplay of trade openness, energy consumption, and gross domestic product (GDP) on carbon emissions across different income groups, analysing data from 163 countries from 2000 to 2019. Using panel regression and multiple linear regression techniques, the findings highlight energy consumption as the principal driver of carbon emissions across all income categories, underscoring its central role in environmental sustainability challenges. High-income countries, despite technological advancements, continue to exhibit substantial emissions due to their reliance on fossil fuels. In contrast low-income nations face difficulties in balancing economic growth with environmental sustainability, often lacking the resources to adopt cleaner energy alternatives. The study emphasises the urgent need for income-specific strategies to reduce carbon emissions, advocating for the widespread adoption of renewable energy sources and tailored policy interventions. These insights align with the United Nations Sustainable Development Goals, particularly SDG 13 (Climate Action), by promoting the integration of economic development with environmental stewardship. By addressing disparities across income levels, this research offers actionable recommendations for policymakers to support equitable and sustainable practices globally.

Keywords Carbon emission · Energy consumption · Trade openness · Economic growth · Environmental sustainability · Panel regression analysis

1 Introduction

The rise in carbon emissions driven by global industrialisation has triggered environmental pollution, global warming, and climate change [4]. High-income countries such as China are experiencing rapid growth in carbon emissions across various sectors, with projections suggesting they will reach peak emissions by 2030 [19, 36, 42, 65, 67, 68]. In contrast, despite notable economic growth, low-income countries contribute only 1.6% to global carbon emissions, with projections estimating 8% of per capita emissions by 2030 [29]. This rising atmospheric concentration of carbon emissions significantly impacts countries across all income groups.

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Trade openness which measures a country's engagement in international trade, influences productivity and economic growth. Its contribution depends on its relative weight in economic activity [44]. Over the past two decades, world trade has grown at an average of six percent per year—twice the pace of global output—indicating sustained expansion [61]. Some developing nations have increasingly opened their economies to reap the benefits of trade-driven development [46]. Consequently, countries with higher trade openness are expected to outperform those with lower levels [64]. Notably, developing economies have expanded their share in global trade, with countries like Singapore leading the way [56]. However, many low-income nations must further enhance trade participation to stimulate economic growth [61].

Energy consumption is another crucial factor affecting environmental quality and human well-being in the developing world [31, 119]. As populations and industries grow, energy demands rise, leading to increased greenhouse gas emissions in many countries [75, 93]. Consequently, nations such as China, India, the USA, and Russia have become the world's leading energy consumers [6].

For instance, the United Arab Emirates (UAE), a high-income country, heavily relies on oil and gas exports, which account for 30% of its Gross Domestic Product (GDP), and has not yet implemented significant plans for transitioning to renewable energy [9]. The UAE also faces rising energy efficiency challenges due to population growth, increasing economic activity, and unsustainable consumption patterns [85]. Similarly, oil revenues significantly contribute to Oman's GDP, reflecting a continued dependence on fossil fuels [106]. Although energy use has increased across all income groups, high-income countries consume nearly five times more energy per capita than their lower-income counterparts [103]. Nevertheless, modern societies increasingly depend on reliable, secure electricity for economic growth, which encourages the adoption of more efficient and less carbon-intensive technologies [37, 103].

GDP, a widely used measure of economic performance, is closely linked to carbon emissions, especially in high-income countries undergoing rapid industrialisation [108]. Singapore, for example, has experienced high per capita growth with an open economy. In 2017, it was ranked the world's second most open and pro-business economy [102]. On the other hand, for countries like Ethiopia, achieving meaningful poverty reduction requires policies that support faster economic growth [104].

This study aims to provide a comprehensive empirical assessment of how trade openness, energy consumption, and GDP products affect carbon emissions in 163 countries across four income groups between 2000 and 2019. By categorising nations into high-income (54), upper-middle-income (44), lower-middle-income (46), and low-income (19) groups, the study offers a nuanced understanding of how these economic factors influence carbon emissions at different stages of development.

What sets this study apart is its examination of the differential impacts of trade openness, energy use, and economic growth on carbon emissions across income levels—an area often overlooked in existing literature, which tends to focus on global or region-specific trends. In contrast, this study employs both multiple linear regression and panel regression models, enabling more accurate estimation across income categories. Additionally, graphical trend analysis enhances the visualisation of emission trajectories.

By spanning 163 countries over two decades, this study provides robust, policy-relevant insights to support sustainable development. Its findings are particularly valuable for policymakers, highlighting the need for differentiated trade and economic policies tailored to each income group. This is vital to achieving the United Nations' net-zero carbon emissions target by 2050 and ensuring equitable access to affordable, clean energy for all.

1.1 Theoretical framework

The relationship between carbon emissions, GDP, energy consumption, and trade openness can be comprehensively explained through three main theories: (1) the Environmental Kuznets Curve (EKC), (2) the Pollution Haven Hypothesis, and (3) the 3Ps Framework of Sustainability.

The EKC posits a dynamic relationship between per capita income and environmental degradation. It suggests that during the early stages of economic growth—characterised by industrialisation and increased resource consumption—environmental degradation worsens. However, beyond a certain income threshold, societies become more environmentally conscious, leading to improved environmental regulations, technological advancements, and sustainable practices that gradually reduce degradation. This concept is typically illustrated by an inverted "U"-shaped curve, reflecting the rise and subsequent decline of environmental harm as economies develop [36, 51, 110].

The Pollution Haven Hypothesis asserts that multinational corporations relocate pollution-intensive industries to countries with weaker environmental regulations to reduce costs and circumvent stricter environmental standards. While these relocations may offer short-term economic advantages, the theory also suggests that strong environmental regulations can drive the innovation and adoption of cleaner technologies, ultimately enhancing production efficiency and reducing carbon emissions [18, 66].

The 3Ps Framework of Sustainability, also known as the triple bottom line, emphasises three interconnected dimensions: People, Profit, and Planet.

- The "People" dimension highlights the social aspect of sustainability, focusing on the impact of corporate and economic activities on various stakeholders, including employees, communities, and the broader society. It stresses the importance of promoting social welfare and ensuring a positive societal impact.
- The "Profit" dimension pertains to the economic viability of actions, underscoring the importance of financial performance for long-term business sustainability. This dimension advocates for achieving profitability while maintaining ethical and socially responsible practices.
- The "Planet" dimension considers the environmental consequences of human activities. It promotes eco-conscious decision-making, encouraging measures that minimise environmental harm—particularly carbon emissions—and support ecological wellbeing.

Within this framework, the "People" aspect underscores the social implications of key variables, recognising that rising GDP and energy consumption may improve living standards while simultaneously increasing carbon emissions, thereby affecting public health and quality of life. The "Profit" element acknowledges the role of economic growth in generating wealth, while also highlighting the potential trade-offs associated with higher emissions. The "Planet" component demands a critical examination of environmental outcomes, particularly concerning carbon emission. It calls for targeted interventions such as transitioning to renewable energy and implementing regulations that promote sustainable business practices.

Balancing these three dimensions is essential to achieving sustainability across national economies [15, 38, 80]. The framework ultimately reflects the intricate interplay between economic growth and environmental sustainability, suggesting that while early development may exacerbate environmental harm, long-term prosperity can foster more eco-friendly societal choices.

The remainder of this paper is structured as follows: Sect. 2 presents a literature review highlighting key findings and gaps in past studies; Sect. 3 details the data sources and methodology; Sect. 4 discusses the results and their implications; and Sect. 5 concludes with policy recommendations.

2 Literature review

As shown in Fig. 1, databases such as Emerald Insight, Google Scholar, Scopus, ScienceDirect, and Web of Science were used to search for relevant literature using the study's keywords. After a thorough review, 87 articles were selected based on journal ranking and relevance to the study scope.

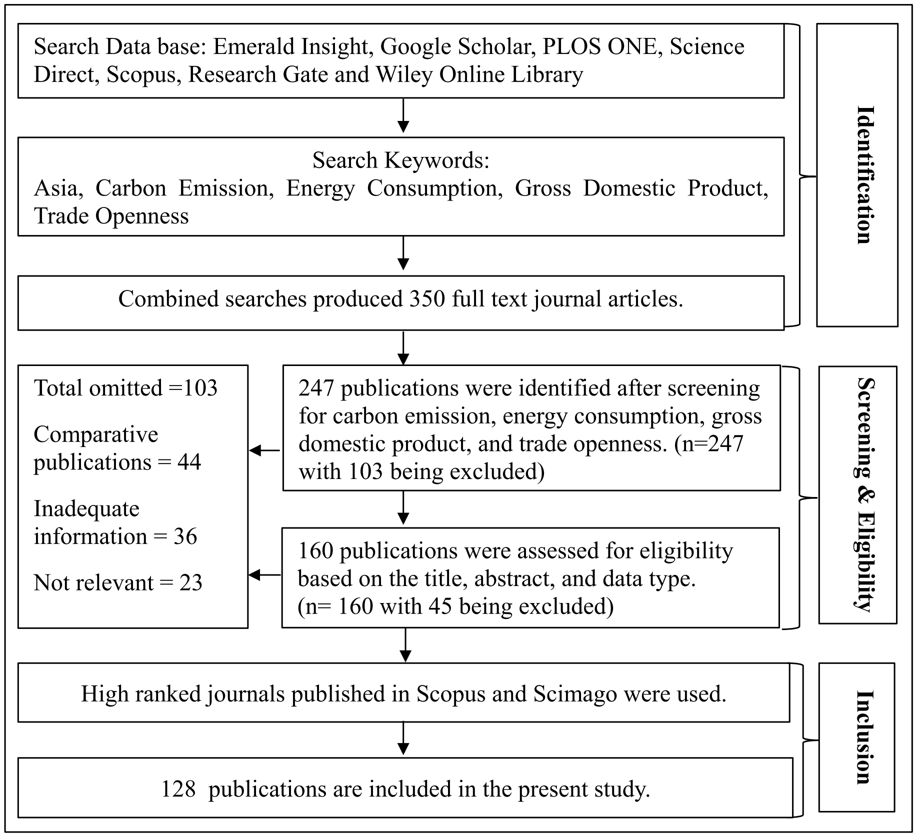
Climate change is now one of the most pressing global concerns [1]. Economic activity contributes significantly to carbon emissions, which in turn drive climate change. Understanding the relationship between key economic indicators and carbon emissions is vital for fostering sustainable growth. This literature review explores the effects of trade openness, energy consumption, and GDP on carbon emissions across income-based country groups.

2.1 High income countries

Most high-income countries prioritise economic development, but this often comes at the cost of significantly increased carbon emissions, which create considerable environmental and public health challenges [17, 71, 98, 111]. The evolution of technology, improvements in energy efficiency, and growing urbanisation have notably changed the dynamics of CO_2 emissions in modern societies compared to earlier industrial periods [6, 21–28, 32, 114].

In addition, trade openness plays a pivotal role in increasing carbon emissions [83, 95]. Its environmental impact differs by income level, but in high-income countries, greater trade openness is often associated with energy-intensive industrial processes that drive higher carbon emissions [35, 94, 111]. The growth in trade volume and deeper economic integration typically exacerbate emission levels [40, 72, 73].

Fig. 1 Search Strategy and Classification of Publication. Source: Authors' illustration



Energy consumption is a major contributor to carbon emissions across all income groups, and the correlation between the two is particularly evident in high-income nations where fossil fuels still dominate the energy mix [50, 69, 79]. These countries are characterised by higher levels of energy consumption, driven largely by rapid industrialisation and urbanisation [31], which in turn lead to elevated emissions.

The impact of GDP on carbon emissions is complex in high-income countries. As national wealth increases, energy consumption also tends to rise, often relying heavily on fossil fuels, thereby contributing further to emissions. Moreover, the importation of environmentally harmful goods to sustain economic growth aggravates long-term carbon emissions [12, 40]. Consequently, while high-income countries pursue economic expansion, they must simultaneously adopt energy-efficiency measures to mitigate their carbon footprints [22, 41]. Several country-specific examples illustrate these trends:

- Japan ranks among the top five carbon-emitting countries globally, primarily due to economic activities aimed at boosting GDP [10, 100].
- The UAE continues to rely heavily on fossil fuels for energy generation and oil and gas production, contributing to global warming and climate change [86].
- Singapore, a newly industrialised country, emits high levels of CO_2 due to substantial energy demand [97, 117].
- The UK, like other high-income nations, consumes large amounts of energy for electricity production [59].
- Kuwait experiences increased carbon emissions and energy consumption as it accelerates economic growth, resulting in extreme weather events such as high temperatures [92, 113].

2.2 Upper middle-income countries

Environmental research increasingly examines the impact of trade openness, energy consumption, and GDP on carbon emissions, particularly by analysing different income groups to identify key contributing factors. Upper-middle-income countries are significant emitters of carbon dioxide into the atmosphere [16]. While increased trade can lead to higher energy consumption and greater carbon emissions, it may also promote the transfer of cleaner technologies and the adoption of improved environmental standards, thereby potentially reducing emissions [111].

The overall effect of energy efficiency on CO_2 emissions varies across income groups and over time. In upper-middle-income nations, fossil fuels continue to dominate the energy mix. However, implementing energy efficiency measures can help decouple energy consumption from emissions [23, 54, 115]. These countries often prioritise GDP growth over environmental concerns in their pursuit of economic stability.

The Environmental Kuznets Curve (EKC) hypothesis proposes an inverted U-shaped relationship between GDP and environmental degradation. However, the strength and validity of this relationship differ depending on income level and pollutant type [78]. Similarly, the Environmental Phillips Curve (EPC) suggests that GDP growth and increased energy consumption contribute to environmental degradation in many upper-middle-income countries, such as Turkey [116]. As a result, efforts to enhance GDP often come at the cost of increased carbon emissions. For example:

- Suriname, an upper-middle-income country, increases energy consumption to support economic growth, which in turn leads to higher CO_2 emissions [8, 58].
- In the Dominican Republic, studies have shown a significant positive relationship between energy consumption, GDP, and carbon emissions—largely attributable to industrial and economic activities [47, 117].

2.3 Lower middle-income countries

Understanding the relationship between trade openness and carbon emissions in lower-middle-income countries is essential for promoting sustainable development and mitigating the effects of climate change. Generally, higher levels of trade openness are correlated with increased carbon emissions [33]. Research has established a positive relationship between energy use and carbon emissions in this income group, indicating that economic expansion is closely tied to increased energy consumption [70].

Decoupling economic growth from carbon-intensive energy sources remains a significant challenge. Nevertheless, implementing energy efficiency initiatives and transitioning to renewable energy are vital steps in reducing environmental impact [60]. GDP and carbon emissions are also closely linked in lower-middle-income countries. While some of these countries are adopting cleaner technologies and introducing environmental legislation during periods of rapid economic growth, such progress often still results in increased emissions [101]. For example:

- Bangladesh, a lower-middle-income country, is experiencing the adverse effects of climate change, largely driven by its growing carbon emissions. Key contributors include rising energy consumption and rapid urbanisation [5, 55].
- Sri Lanka also demonstrates a significant increase in carbon emissions due to economic activities aimed at achieving macroeconomic stability and development [48].

2.4 Low income countries

Low-income countries face significant challenges in adopting renewable energy technologies, largely due to financial constraints, which in turn contribute to elevated levels of carbon emissions. However, technology transfer—through foreign investment and international cooperation—has the potential to support access to cleaner technologies and reduce emissions [42]. The impact of trade openness on carbon emissions in these countries varies, depending on factors such as technological adoption, energy efficiency, and the strength of environmental regulations. Nevertheless, a positive correlation between trade openness and carbon emissions is commonly observed in low-income countries [39, 70, 77].

- In Mali, for instance, population growth and economic expansion, combined with low incomes, inefficient energy use, and heavy dependence on fossil fuels, have created serious challenges regarding carbon emissions [74].

The literature highlights the need for further empirical studies focused specifically on low-income countries to better understand and reduce CO_2 emissions within this context.

The income-based literature review presented above clearly demonstrates that trade openness has varying effects on carbon emissions across income groups; energy consumption is a major contributor to emissions in all categories; the relationship between GDP and carbon emissions is nuanced and varies by development stage.

Further research is essential to inform strategies that support sustainable development and climate action in all income categories.

2.5 Sustainable development and global implications

This study contributes to the broader goals of the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action). High-income countries are well-positioned to invest in research, development, and innovation to mitigate carbon emissions without compromising economic stability. Countries such as the USA, Germany, and Japan, among the highest CO_2 emitters, should scale up investments in renewable energy. Green investments and innovations are key strategies for all income groups to reduce emissions. Maintaining environmental quality is more feasible when sustainable, green practices are mainstreamed [21, 24, 28].

In upper-middle-income countries such as Turkey and Brazil, rapid industrial development and natural resource use can lead to increased pollution. These countries must adopt cleaner technologies and maintain energy security while pursuing environmental sustainability [25, 26].

However, all income groups bear shared responsibility in the transition to low-carbon economies. Low-income countries, in particular, often prioritise economic development over environmental sustainability, but this trade-off is not sustainable in the long term. This study offers policy-relevant insights for all income groups, supporting the design of income-specific strategies to achieve the UN's Net Zero carbon emission target by 2050.

2.6 The role of technology in emission reduction

In the modern context, technological advancement plays a pivotal role in reducing emissions by improving industrial efficiency, minimising energy consumption, and enabling sustainable development. Artificial Intelligence (AI), for example, has emerged as a transformative tool for environmental sustainability by optimising industrial processes and reducing carbon footprints [88].

The semiconductor industry, which underpins AI and digital transformation, also contributes to renewable energy development through innovations in smart grid technologies and efficient energy storage systems [91]. Meanwhile, technological trade and structural industrial upgrades have supported sustainable growth in high-income countries, demonstrating how green innovation can decarbonise economies [87].

Emerging economies can strike a balance between technological progress and environmental conservation by leveraging market mechanisms and effective resource management [105]. In Asian economies, the integration of renewable energy with information and communication technology (ICT) has accelerated industrial transformation, enhanced green energy production, and reduced environmental degradation.

Across all income levels, green innovation, supported by digital and AI technologies, is essential for transitioning to a carbon–neutral future and fostering sustainable global manufacturing [87, 88].

3 Materials and methods

This section outlines the data sources used to study each variable, as well as the analytical model employed in the research.

3.1 Data and variables

The study analysed panel data from 163 countries over the period from 2000 to 2019, with countries categorised into income groups based on classifications from the year 2022 [81]. Data availability was prioritised using the Our World in Data platform, which provided consistent, cross-country measures for the variables under investigation. Table 1 summarises the variables, their units of measurement, and their respective data sources.

Trade openness, measured as a percentage of GDP, is commonly used in cross-country empirical research [95, 111] and serves as a proxy for a country's integration into the global economy. While it may not capture nuances such as trade composition or balance, it offers a consistent and accessible indicator across the 163 countries for the 2000–2019 period. Similarly, energy consumption is expressed in kilowatt-hours per capita, providing a general view of energy usage intensity across populations. Although this measure does not reflect energy efficiency gains or sector-specific energy use, it aligns with the study's focus on broad income group comparisons and responsibilities regarding carbon

Table 1 Data sources and variables

Variable	Measure	Data source
Carbon Emission (CE)	Metric Ton Per Capita	Our World in Data https://ourworldindata.org/grapher/co-emissions-percapita
Trade Openness (TO)	Percentage of GDP	https://ourworldindata.org/grapher/trade-as-share-of-gdp
Energy Consumption (EC)	Thousands of Kilowatt Hours Per Capita	https://ourworldindata.org/grapher/per-capita-energy-use
Gross Domestic Product (GDP)	Thousands of Dollars Per Capita	https://ourworldindata.org/grapher/gdp-per-capita-worldbank

Source: Authors' illustration based on Our World in Data [82]

emissions. Future research may consider refining this approach using metrics such as energy intensity (energy use per unit of GDP) or incorporating interaction terms (e.g., TO × energy intensity).

Based on a comprehensive review of relevant literature, the study adopts thousands of dollars per capita and thousands of kilowatt-hours per capita as the units for GDP and energy consumption, respectively. This decision was made to reduce decimal complexity in the multiple linear regression (MLR) outputs. Carbon emissions are measured in metric tons per capita, and trade openness remains measured as a percentage of GDP.

To address gaps in the dataset between 2000 and 2019, the study used a backward forecasting method. Initially, line graphs were constructed based on available data, from which trendlines and corresponding equations were derived. The temporal variable ('x') in these equations was then replaced with backward values to estimate missing observations, ensuring completeness and consistency in the dataset.

Several countries had missing data for specific years. For example, Nauru lacked GDP data from 2000 to 2003 and trade openness data from 2000 to 2007. The United Arab Emirates had a missing value for trade openness in 2000, while Kiribati lacked the same in 2019. Somalia had missing GDP and trade openness data for the period 2000–2012. Trade openness data were also unavailable for Lesotho from 2000 to 2006, Myanmar from 2000 to 2009, and Papua New Guinea from 2005 to 2019. Timor-Leste had missing carbon emissions data for 2000–2001 and energy consumption data for 2000–2002. Tunisia lacked trade openness data in 2019, and Dominica had missing data for trade openness between 2000 and 2008 and again in 2019. Similarly, Equatorial Guinea had no trade openness data from 2000 to 2004, and Guyana from 2006 to 2019. Montenegro and Serbia lacked energy consumption data for the years 2000–2005, while Suriname had missing trade openness data for 2000–2005 and 2011–2019. Laos (2017–2019), Maldives (2000–2013), Samoa (2000–2001), and Tajikistan (2015–2016) also had missing trade openness data for the specified periods.

By applying this method, the study was able to construct a complete and coherent panel dataset suitable for the regression analyses conducted across different income levels.

3.2 Analytical model

To examine the impact of trade openness, energy consumption, and GDP on carbon emissions, this study employed a panel regression technique. Two regression equations were used—Eqs. (1) and (2)—to produce the study's core results. In both equations, carbon emissions (CE) serve as the dependent variable, while trade openness (TO), energy consumption (EC), and gross domestic product (GDP) are treated as the independent variables.

Equation (1) utilises a panel data structure and was applied to assess the relationship within each income group. Specification tests for panel data models were conducted to determine the most appropriate estimator—either a fixed effects or random effects model. The following equation represents the panel regression model used for group-level analysis:

$$\mathrm{CE}_{it} = \beta_0 + \beta_1 \mathrm{TO}_{it} + \beta_2 \mathrm{EC}_{it} + \beta_3 \mathrm{GDP}_{it} + \varepsilon_{it} \tag{1}$$

Here, i denotes the income group, t represents the year, ε_{it} is the error term, and β_0 to β_3 are the model coefficients.

In addition to the panel analysis, Eq. (2) presents a Multiple Linear Regression (MLR) model, which was used for individual country-level analysis. The aim was to provide clearer insights into national-level dynamics:

$$CE_t = \alpha_0 + \alpha_1 TO_t + \alpha_2 EC_t + \alpha_3 GDP_t + \tilde{a}_t \tag{2}$$

This single-country model allows a cross-sectional view over the entire study period by averaging each variable across the years. It helps identify countries where trade openness, energy consumption, or GDP had the most significant positive effects on carbon emissions. The study summarised these results—particularly the strongest positive coefficients—into a comparative table to enhance interpretability.

To perform the empirical analysis, the study utilised STATA software, applying appropriate regression tools and diagnostics to ensure robustness.

While panel regression facilitated the exploration of income-group and overall global patterns over time, the use of MLR enabled country-specific assessments. Since many environmental and economic policies are formulated at the national level, the inclusion of MLR adds practical value by offering country-level insights. This dual-method approach allows for both macro-level comparisons and micro-level policy recommendations, supporting a more nuanced understanding of the trade–energy–growth–emissions nexus.

4 Results

This section presents a descriptive analysis of the core variables—TO, EC, GDP, and CE—across global income groups. A comprehensive summary is first provided, followed by visual analyses and supplementary descriptive statistics to contextualise the trends observed from 2000 to 2019.

4.1 Descriptive analysis

Descriptive statistics for all countries and each income group are summarised in Table 2. The complete dataset includes 3,260 observations, of which 1,080 belong to high-income countries, 920 to lower-middle-income countries, 880 to upper-middle-income countries, and 380 to low-income countries.

Table 2 highlights notable contrasts across income groups. High-income countries recorded the highest average GDP (41.23 thousand USD per capita), the highest average energy consumption (60.56 thousand kWh per capita), and the highest average trade openness (108.32% of GDP). Unsurprisingly, they also exhibited the highest mean carbon emissions (10.39 metric tonnes per capita), underscoring the disproportionate environmental footprint of high-income economies.

To further illustrate variable dynamics across time and income groups, the study constructed Fig. 2, which visualises average annual values for each variable from 2000 to 2019. For this, average values were calculated by income group for each year using all countries within each classification. These line graphs reveal general fluctuations and patterns in CE, TO, EC, and GDP over the study period, offering visual insights into economic and environmental transitions.

In addition to the time series graphs, the study also computed average values for each country across two key periods—2000–2005 and 2015–2019—for all four variables. These averages were used to generate world maps, presented in Appendix S2, which highlight how carbon emissions, trade openness, energy use, and GDP levels evolved spatially across income groups over the study period. The visual comparison underscores both improvements and persistent disparities in economic and environmental indicators across global regions.

4.2 Panel data regression and multiple linear regression analysis

The results of the panel data model specification tests, based on Eq. (1), are presented in Table 3. The F-test and the Breusch-Pagan test were conducted to evaluate the appropriateness of using pooled ordinary least squares (POLS). For all countries and each income group, the results rejected the null hypothesis, confirming that the POLS approach is unsuitable for the current study.

Subsequently, the Hausman test was employed to determine the more appropriate model between fixed effects (FE) and random effects (RE). The null hypothesis of the Hausman test was rejected for all country groups—including high-income, upper-middle-income, lower-middle-income, and low-income—indicating that the fixed effects model is more efficient. Therefore, the FE model was adopted as the most appropriate specification for all panel regressions conducted in this study.

Given that the FE model was found to be most suitable, both FE and RE estimates are provided in Appendix S3 for comparison. Based on FE estimates, energy consumption emerged as the only independent variable with statistically significant positive effects on carbon emissions across all income groups—including high-income, upper-middle-income, lower-middle-income, and low-income countries.

Table 2 Summary of descriptive statistics for income groups

Income Groups		Variables			
		CE	GDP	EC	TO
All Countries	Obs	3260	3260	3260	3260
	Mean	4.874597	18.89011	26.55065	88.48111
	SD	6.295976	20.11825	35.20371	50.06225
	Min	0.019352	0.2408	0.1051101	− 49.5272
	Max	62.25897	120.6478	262.5857	437.3267
High Income	Obs	1080	1080	1080	1080
	Mean	10.39081	41.22669	60.56064	108.3168
	SD	7.779584	20.04528	42.60442	65.2959
	Min	1.367556	0.8681	13.37731	19.5596
	Max	62.25897	120.6478	262.5857	437.3267
Low Income	Obs	380	380	380	380
	Mean	0.1758955	1.90474	1.068346	60.74382
	SD	0.1784168	1.089565	1.076794	26.59032
	Min	0.019352	0.2408	0.1051101	1.218845
	Max	1.317864	5.552845	6.385899	156.8618
Lower Middle Income	Obs	920	920	920	920
	Mean	1.414526	5.32126	6.503063	76.82378
	SD	1.832654	3.353021	7.313048	37.03495
	Min	0.074624	0.948782	0.3412	− 49.5272
	Max	15.2814	19.49941	37.68818	211.4998
Upper Middle Income	Obs	880	880	880	880
	Mean	3.751037	12.99722	16.77369	88.30194
	SD	2.90249	5.47113	9.595094	36.89647
	Min	0.690154	3.451679	2.574472	21.85225
	Max	17.89939	41.24949	64.10495	220.4068

Note: Obs., SD, MIN, and MAX define Observations, Standard Deviation, Minimum and Maximum, respectively. CE, GDP, EC and TO define carbon emissions, gross domestic product, energy consumption and trade openness respectively

Source: Authors' Compilation

In addition to the panel regression, the study conducted a Multiple Linear Regression (MLR) analysis for individual countries using Eq. (2). These results are presented in Appendix S4, and Table 4 summarises the countries with statistically significant positive coefficients for trade openness, energy consumption, and GDP.

Table 4 illustrates the direction and strength of relationships between each independent variable and carbon emissions at the country level. For example, a positive coefficient for energy consumption indicates that, holding other variables constant, increases in energy consumption lead to higher carbon emission.

In Sri Lanka, the energy consumption coefficient (0.2239) implies that a one-unit increase in per capita energy consumption (measured in thousands of kilowatt hours) results in a 0.22 metric tonne increase in CO_2 emissions per capita. Similarly, in Lithuania, the MLR model shows positive coefficients for all three variables—trade openness (0.0427), energy consumption (0.0329), and GDP (0.8027)—highlighting that GDP exerts the strongest influence on carbon emissions in that context. This suggests that economic expansion in Lithuania has a significantly greater carbon impact than trade or energy use alone.

These examples emphasise the importance of interpreting both the sign and magnitude of regression coefficients in light of national economic structures, energy portfolios, and consumption behaviours.

Despite technological advancements, high-income countries continue to exhibit higher carbon emissions. This counterintuitive result can be attributed to multiple structural factors. First, improvements in energy efficiency may result in the rebound effect, where reductions in energy use per unit of output are offset by increased total consumption. Second, many high-income nations maintain fossil fuel-based infrastructure, which hampers rapid transitions to clean energy despite innovation. Third, affluent lifestyles in such countries often involve energy-intensive consumption—such as

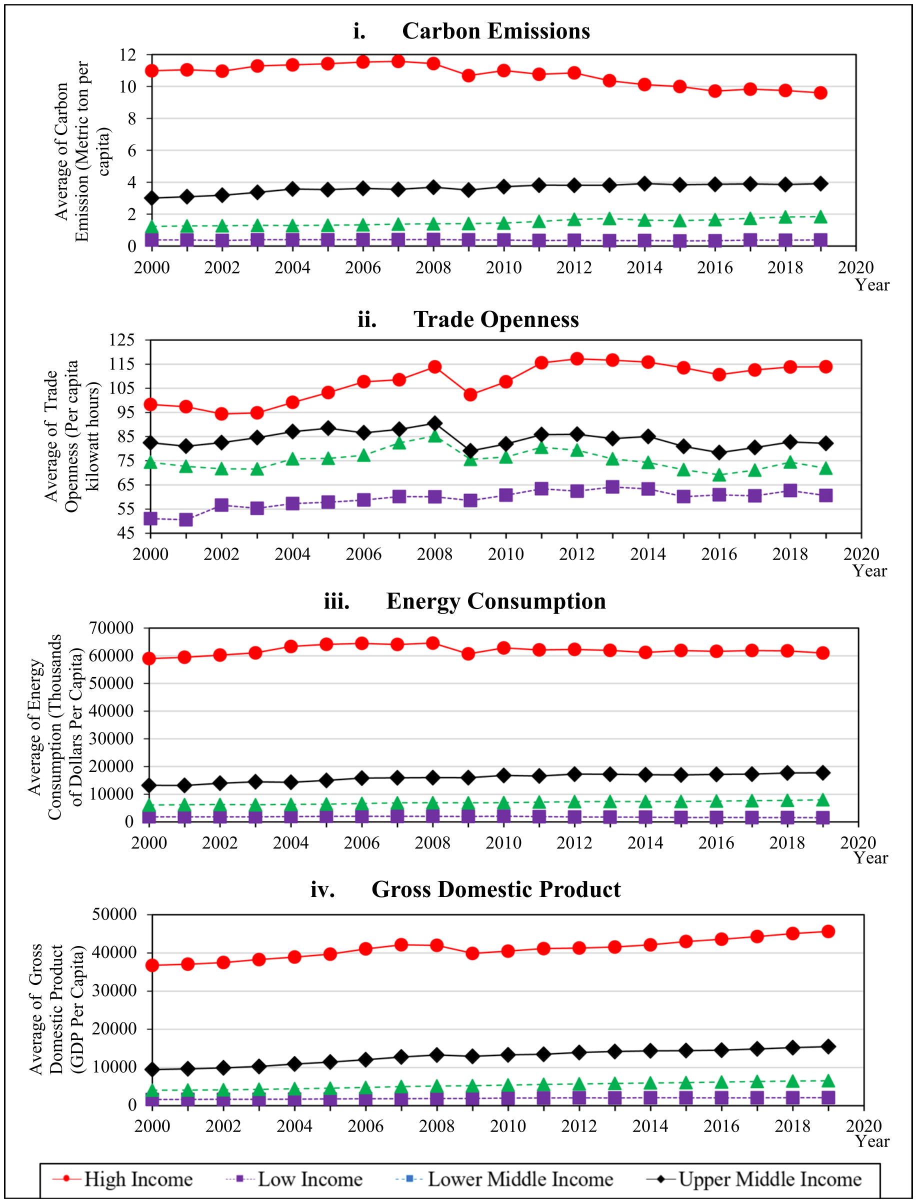


Fig. 2 Income group-wise averaged variables from 2000 to 2019. [82] Source: Authors' illustration based on Our World in Data

Table 3 Specification Test for Panel Data Models

Region	F test H_0: POLS H_1: Fixed effect	Hausman test H_0: Random effect H_1: Fixed effect
All countries	102.68***	170.70***
High Income	108.42***	65.71***
Upper Middle Income	131.95***	20.85***
Lower Middle Income	30.40***	11.97***
Low Income	34.77***	13.62***

Note: The symbols*** represent a 1% significant level

larger living spaces, increased transportation, and higher consumption of goods—all contributing to sustained emissions. These findings suggest that technological innovation alone may be insufficient to achieve emissions reductions without comprehensive changes in infrastructure, policy, and consumption patterns.

Table 4 Summary of positive MLR estimates of income groups of worldwide countries

	Countries	CE			Constant
		TO	EC	GDP	
High Income	Chilie	0.0019	0.1168*	0.0784**	– 0.2657
	Lithuania	0.0127***	0.0427**	0.0329***	0.8027*
	Oman	0.1031*	0.2229***	0.0230	– 12.2463***
	Seychelles	0.0011	0.0446***	0.1442***	– 0.7787
	Uruguay	0.0230***	0.0515	0.0204	– 0.5142
Upper Middle Income	Albania	0.0089	0.0442	0.0716***	– 0.3380
	Argentina	0.0143**	0.0349	0.1107**	0.6111
	Armenia	0.0009	0.0927***	0.0521*	– 0.1196
	Dominican Republic	0.0060	0.1574***	0.0278	– 0.0011
	Equatorial Guinea	0.0379	0.1055	0.0332	– 1.6415
	Fiji	0.0025	0.0948***	0.1226***	– 1.2977***
	Gabon	0.0013	0.0862***	0.4298***	– 4.4428***
	Montenegro	0.0093*	0.1102***	0.1465***	– 2.6247**
	Suriname	0.0070	0.0028	0.1391	0.7605
	Turkmenistan	0.0191**	0.0216	0.4667***	3.8902**
Lower Middle Income	Bangladesh	0.0006**	0.1747***	0.0184	– 0.0249***
	Bolivia	0.0025*	0.0578*	0.2772***	– 0.9374***
	Cameroon	0.0014	0.1931**	0.1775***	– 0.6694***
	Egypt, Arab Rep	0.0037**	0.1246**	0.0997***	– 0.1248
	Ghana	0.0002	0.0006	0.1002	0.0144
	Haiti	0.0026**	0.0699	0.1330	– 0.3493*
	Honduras	0.0021**	0.0179	0.1686**	– 0.1701
	Kyrgyzstan Republic	0.0023	0.0839*	0.4081***	– 1.6083**
	Mauritania	0.00009	0.1886***	0.0397	– 0.1023
	Mongolia	0.0056	0.8375**	0.9715***	– 17.4632***
	Nepal	0.0039***	0.2856***	0.0509***	– 0.3783***
	Senegal	0.0006	0.0509	0.4491***	– 0.8827***
	Sri Lanka	0.0014	0.2239**	0.0081	– 0.2422
	Tajikistan	0.0029	0.0977**	0.5747***	– 2.0091***
	Tanzania	0.0002	0.1257***	0.0623***	– 0.0829***
	Timor- Leste	0.0009	0.2595**	0.0403	– 0.1373
	Zimbabwe	0.0004	0.1902***	0.0945***	– 0.2628**
Low Income	Ethiopia	0.0010**	0.2315***	0.0018	– 0.0873**
	Mali	0.0013***	0.0816***	0.0245	– 0.0446
	Mozambique	0.0017*	0.0676	0.0392	– 0.1937***
	Somalia	0.0002	0.2930***	0.0103	– 0.0624
	Uganda	0.0001	0.0829***	0.0522***	– 0.0522***

Note: *Significant at 10%, ** significant at 5%, and ***significant 1% significance level; MLR denotes Multiple Linear Regression

Although the Environmental Kuznets Curve (EKC) was discussed in the literature review, this study did not include non-linear terms (e.g., GDP squared) in the regression model. The decision was based on the study's aim to present cross-sectional and income group-based comparisons using a linear framework. However, future research could extend this analysis by incorporating non-linear specifications to directly test the EKC hypothesis and evaluate the presence of an inverted U-shaped relationship between GDP and carbon emissions across income levels.

5 Discussion

The descriptive analysis (Table 2) reveals clear disparities in GDP growth, energy consumption, and trade openness among income groups, with high-income nations contributing the most to global carbon emissions. High trade openness (mean = 108.32), elevated GDP (mean = 41.23), and high energy consumption (mean = 60.56) underscore the energy-intensive nature of economic activity in these countries. The fact that 54 high-income countries contribute significantly to global carbon emissions highlights the urgent need for targeted interventions—such as carbon taxes, green technology incentives, and sustainable trade practices. In leading the global low-carbon transition, high-income nations must also prioritise technology transfer and financial support for lower-income countries.

As depicted in Fig. 2i, carbon emissions in high-income countries increased steadily from 2000 to 2019, consistent with prior findings [76]. This trend is largely attributed to sustained economic expansion, which has led to greater industrial output and rising energy demand. A continued reliance on fossil fuels, resource-intensive production, and consumption patterns further exacerbated emissions. While some high-income countries have made strides toward sustainable practices, economic growth often supersedes environmental priorities. Additionally, the top three carbon emitters—China, India, and the USA—fall within or near the high-income classification, reinforcing the link between higher income and higher emissions [34]. Comparatively, the other three income groups display lower carbon emission levels.

Figure 2ii shows that high-income countries also lead in energy consumption, a consequence of industrial development, rising consumer demand, technological advancement, and urbanisation. Expanding cities, larger homes, increased mobility, and industrial production have significantly raised energy needs [99, 109]. However, the ecological effectiveness of this consumption remains limited. This pattern underscores the need for strong policy frameworks to ensure sustainable economic growth alongside a shift to environmentally friendly energy sources [107]. Despite some progress in improving energy efficiency and promoting renewable energy, high-income countries' economic and lifestyle trends continue to drive energy demand [20]. In contrast, lower-income countries exhibit lower energy usage due to resource constraints and limited capacity to meet demand.

As shown in Fig. 2iii, high-income countries have achieved significantly higher GDP levels, driven by technological innovation, global integration, infrastructure development, and political stability [62]. Among the remaining groups, upper-middle-income countries exhibit increasing GDP levels due to economic reforms, resource access, and skilled labour forces [14]. In contrast, low- and lower-middle-income countries, though growing, face persistent challenges including limited capital, infrastructure gaps, and weak institutions. In these regions, GDP correlates positively with carbon emissions, highlighting the urgent need for environmental regulations and carbon mitigation strategies [53].

Figure 2iv indicates an upward trend in trade openness across all income groups, reflecting globalisation and the adoption of business-friendly trade policies [43]. Access to global markets, higher export potential, and increased foreign investment have contributed to this trend. Nevertheless, greater trade openness is also linked to heightened emissions, especially where trade is concentrated in energy-intensive goods and services. Thus, the figures collectively illustrate that carbon emissions are closely tied to GDP, energy consumption, and trade openness across income categories.

When comparing 2000–2005 and 2015–2019, stark differences emerge across income groups. High-income nations continued to exhibit substantial carbon emissions [118], reaffirming the income–emissions link. For example, Qatar's fossil fuel dependence led to a surge in emissions, though it witnessed a slight decline in the latter period [3, 52]. Kuwait, through adherence to global agreements and strategic reforms, reduced its emissions [11, 65]. The UAE, via proactive energy policy and renewable investment, also showed progress in lowering emissions [13, 57].

In terms of trade, Singapore led during 2000–2005, while Luxembourg took the lead in 2015–2019, due in part to its robust financial sector. However, studies show that increased trade openness is often accompanied by higher emissions. Emerging technologies, especially artificial intelligence, are further shaping energy transitions and trade patterns, creating complex financial and environmental implications, particularly in oil-exporting countries [49, 112]. Despite these challenges, countries such as Bahrain and the UAE have begun to reduce their carbon footprints through improved energy efficiency and economic diversification.

In reviewing Table 4, a large number of lower-middle-income countries display positive relationships between carbon emissions and the independent variables. Among high-income countries, nations such as Chile exhibited a strong positive relationship between carbon emission, trade openness, and energy consumption, affirming the emissions burden of energy use and international trade. As previously documented, UAE and Oman also show that energy consumption and industrialisation are key emission drivers [2, 7, 8, 30, 86]. Meanwhile, Lithuania demonstrated positive and significant relationships with all three variables, underscoring the complexity and diversity of factors within high-income economies [45].

Within upper-middle-income countries, the picture is more nuanced. For instance, Albania showed a positive relationship with GDP but negative associations with trade openness and energy consumption, suggesting possible trade-offs between growth and emissions reduction [4, 63]. In contrast, Argentina demonstrated positive links with both trade openness and GDP, while Armenia highlighted the influence of energy consumption. These variations indicate that income-level classification alone cannot fully predict emission dynamics and that country-specific strategies are essential.

In lower-middle-income countries, Bangladesh displayed strong positive relationships between carbon emission, trade openness, and energy consumption, consistent with literature highlighting the environmental costs of fossil fuel dependence [55]. Similarly, Bolivia showed positive associations with trade and energy consumption but a negative relationship with GDP, suggesting tensions between growth and sustainability [96].

Among low-income countries, Ethiopia presented positive correlations with carbon emission, trade openness, and energy consumption, underlining the need for clean energy alternatives in emerging economies [84], Mali revealed similar relationships, though the impact of GDP was less significant.

These findings reaffirm the challenges low-income countries face in pursuing economic development while safeguarding environmental quality.

Across all income groups, the results reinforce the finding that energy consumption is the primary driver of carbon emissions, aligning with prior studies by Gu et al. [50] and Nguyen and Kakinaka [79]. Similarly, the positive association between trade openness and carbon emissions in many high-income countries supports the conclusions of Shahbaz et al. [95] and Park et al. [83].

In the lower-middle-income category, the relationships observed in countries like Bangladesh and Bolivia are consistent with Afridi et al. [5] and Hasan and Chongbo [55], who document the challenge of decoupling economic growth from environmental degradation in South Asia. This study presents a detailed, income-group-based assessment of how GDP, trade openness, and energy consumption influence carbon emissions, supported by robust statistical techniques and descriptive visualisation. These findings offer valuable insights for policymakers, particularly in crafting context-specific environmental strategies that align with economic development goals. The results underscore the urgency of green investment, technological innovation, and policy reform to mitigate emissions while ensuring inclusive and sustainable growth.

6 Conclusion

This study examined the influence of trade openness, energy consumption, and GDP on carbon emissions across 163 countries over the period 2000 to 2019, employing both panel regression and multiple linear regression techniques to explore emission dynamics across varying economic contexts.

The findings indicate that economic growth significantly contributes to rising carbon emissions, particularly in high-income countries, where prolonged industrial expansion is fuelled by continued reliance on fossil fuels. In contrast, low-income countries face constraints due to limited financial resources to invest in clean and sufficient energy supplies. This imbalance highlights the need for context-sensitive policy interventions to address environmental concerns globally and equitably.

While some countries have successfully implemented economic reforms and renewable energy strategies to curb emissions, most continue to prioritise economic growth over environmental protection. The study emphasises that effective and efficient carbon reduction must become a global priority, regardless of income level.

By exploring how trade openness, energy consumption, and GDP influence emissions at different income levels, the study contributes to an underexplored area in the literature. The use of both panel and multiple linear regression models, complemented by graphical trend analyses, enhances the clarity and precision of emission disparities across income groups. The 20-year span across 163 countries provides policy-relevant insights, particularly with regard to achieving net-zero carbon emissions by 2050 and promoting equitable access to clean energy. However, the study acknowledges its limitations, notably the exclusion of additional variables such as technological advancement, industrial structure, and population factors, as well as data limitations for the most recent years.

6.1 Policy implications

To reduce carbon emissions across all income groups and simultaneously balance economic development, energy use, and trade engagement, the implementation of effective and inclusive policies is essential.

6.1.1 Managerial implications

Policymakers should prioritise green economic instruments, including carbon taxes, circular economy initiatives, and sustainable trade regulations, to decouple economic growth from environmental degradation. Policies such as energy subsidies, rebates, and public–private partnerships can accelerate the transition to renewable energy and reduce dependence on fossil fuels.

Incorporating sustainability standards into trade policies and encouraging eco-labelling can promote low-carbon production and incentivise sustainable consumption. Given income disparities, high-income countries should take the lead by financing green projects and supporting technology transfers to low- and middle-income nations. Instruments like green bonds and sustainable FDI can help bridge environmental financing gaps. Enhancing international cooperation, particularly through multilateral environmental agreements and cross-border knowledge exchange, will further enable an equitable transition to a low-carbon global economy.

6.1.2 Practical/social implications

Reducing emissions in the context of economic growth and trade carries critical social and environmental benefits. Transitioning to renewable energy can lead to cleaner air, reducing respiratory diseases and improving public health, especially in densely populated or industrialised areas. Green policy measures can also create inclusive job opportunities in the renewable sector and ensure access to affordable clean energy for vulnerable communities.

Sustainable trade practices can enhance consumer trust, encourage corporate responsibility, and shift industries toward ethical production models. Further, public awareness campaigns and community-based climate initiatives can play a pivotal role in encouraging sustainable behaviours.

Tailored approaches must also be adopted at the income-group level:

- High-income countries should implement carbon taxes, expand green investments, and champion sustainable trade standards.
- Upper-middle-income countries need to prioritise renewable energy adoption, eco-efficient industrial policies, and energy efficiency mandates.
- Lower-middle-income countries should focus on infrastructure development, economic diversification, and integration into green global value chains.
- Low-income countries require international support through climate finance, off-grid renewable systems, and climate adaptation planning.

Aligning such policies with global sustainability goals will enable countries to achieve economic growth, emissions reduction, and environmental equity simultaneously.

7 Limitations and future research

Despite its valuable contributions, this study acknowledges several limitations. First, data availability and quality, particularly in low-income countries, may affect the accuracy and comparability of results. Variations in data collection methodologies across nations may introduce inconsistency.

Second, although trade openness, GDP, and energy consumption are key drivers, the exclusion of factors such as population growth, urbanisation, technological innovation, and environmental regulation stringency may limit the analytical depth. The macroeconomic lens employed may also obscure important regional and sector-specific variations in carbon emissions.

Third, potential endogeneity and reverse causality between the variables may influence the validity of causal claims, which the current study did not explicitly address.

To overcome these limitations, future research should:

- Incorporate additional explanatory variables such as renewable energy usage, technology adoption, and policy instruments.
- Use sector-specific or region-specific datasets to explore micro-level dynamics.
- Employ advanced econometric techniques (e.g., GMM estimators or instrumental variable approaches) to address endogeneity.
- Evaluate the effectiveness of global climate agreements across income groups to enhance policy relevance.

7.1 Theoretical contribution

This study makes several theoretical contributions to the literature on sustainability, international trade, and environmental economics. It extends the Environmental Kuznets Curve (EKC) framework by assessing whether the relationship between economic growth and emissions differs across income levels, offering empirical support for income-specific trajectories.

By exploring the role of trade openness in shaping carbon emissions, the study contributes to the growing body of research on the trade–environment nexus. Moreover, by integrating energy consumption into the analysis, it bridges the gap between economic and environmental discourses, advancing understanding of how energy use mediates the growth–emissions relationship.

In doing so, the study provides evidence-based recommendations for policymakers and business leaders seeking to balance growth and environmental stewardship. Its multi-level framework offers a nuanced roadmap for implementing income-sensitive policies to support a sustainable, low-carbon future.

Author contributions All authors contributed to the conception and design of the project. RJ, ND and NR composed the writing of the manuscript. ND, VG and DM carried out a significant share of tasks on statistical work in the manuscript. RJ and NR provided critical knowledge in drafting the paper and RJ supervised the entire study. The authors have read and approved the final manuscript.

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Data availability All the data utilised in the analysis is attached as a supplementary material Appendix S1.

Declarations

Ethics approval and consent to participate Not applicable. This study used publicly available secondary data, and no direct involvement of human participants, human tissue, or identifiable personal data was required.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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