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ORIGINAL PAPER

Analyzing the environmental impact of the automobile industry in ASEAN nations

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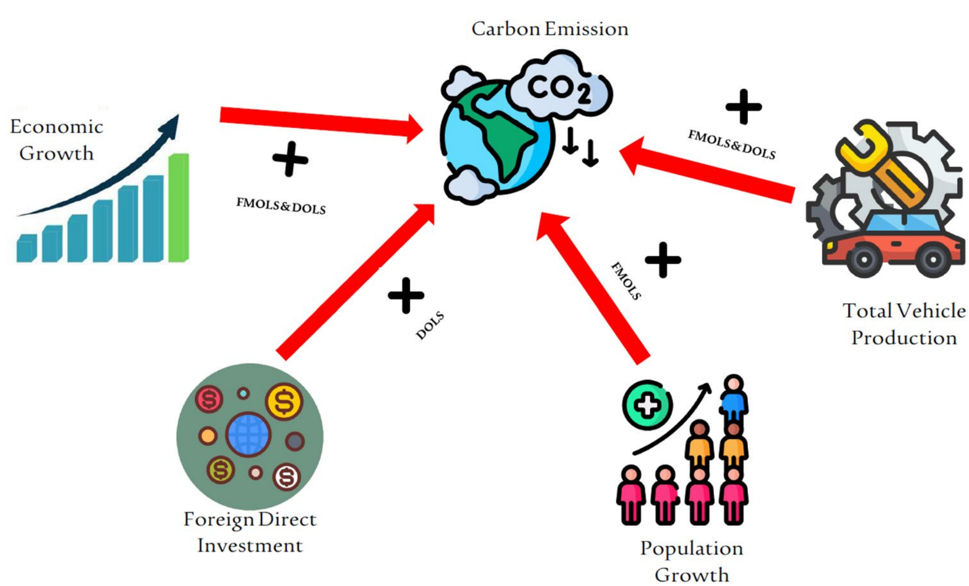
Abstract

Aligned with Sustainable Development Goal 13, this study addresses rising carbon dioxide (CO_2) emissions linked to the automobile industry's expansion in ASEAN nations. Despite the automobile industry's economic significance in ASEAN, its environmental implications have received limited attention. This study investigates the effects of economic growth, foreign direct investment (FDI), population growth, and vehicle production on CO_2 emissions across Vietnam, the Philippines, Indonesia, Malaysia, and Thailand from 1999 to 2022. Using the IPAT model as the conceptual framework, the analysis applies Fully Modified Ordinary Least Squares, Dynamic Ordinary Least Squares, and the Panel ARDL approach to ensure robust estimation and examine long-run relationships. Findings reveal that economic growth, vehicle production, and FDI significantly drive CO_2 emissions, while population growth shows a weaker effect. These results highlight the environmental cost of industrial and economic activities in the region. Policy recommendations urge ASEAN countries to promote sustainable transportation, invest in green technology, and regulate vehicle production to better align economic development with climate goals. The study acknowledges limitations, including the exclusion of renewable energy adoption and environmental regulation indices, and notes that findings may not be fully generalizable beyond ASEAN nations. Future research should expand the model to include broader environmental factors and conduct cross-regional comparisons. This study introduces vehicle production as a novel proxy to assess transportation-induced emissions, alongside economic growth, FDI, and population growth. The findings contribute insights to help ASEAN economies align industrial expansion with sustainability goals.

Graphical abstract



Extended author information available on the last page of the article

Keywords Land transportation · Economic expansion · CO_2 emissions · Linear ARDL · Nonlinear ARDL

Introduction

Data from the International Energy Agency in 2016 reveal a concerning growth in annual carbon dioxide (CO_2) emissions worldwide. From 17.78 billion tonnes in 1980 to 32.10 billion tonnes in 2015, these emissions have increased dramatically. Stern (Stern 2006) accentuated the urgency of tackling greenhouse gas (GHG) emissions (Shaari et al. 2023; Gyamfi et al. 2023). Failed intervention could lead to doubling preindustrial atmospheric GHG levels by 2035. This situation underscores the critical need for proactive measures against climate change. Elevated concentrations of greenhouse gases have led to observable indicators of climate change, including rising global ocean and air temperatures, sea level increases, glacier retreat, and declining species populations (Ghosh et al. 2023; Majekodunmi et al. 2023a; Mohamed Yusoff et al. 2023). Projections suggest that by 2100, Earth's average temperature could surge by 1.2–6.5 °C, accompanied by potential sea level rises of 16.5–53.8 cm, posing a threat to coastal populations worldwide (Bernstein et al. 2007; Lau and Kim 2010).

Transportation, a crucial development component due to its substantial contribution to the gross domestic product (GDP), plays a significant role in CO_2 emissions. To better understand the impact of transportation on environmental degradation, it is important to thoroughly analyze the available facts and data**.** At the center of this examination is a deeper investigation into the intricate interplay between vehicle production and the release of carbon dioxide. By delving into this complex linkage, insights can be gleaned into how the operation of various vehicles contributes to the larger landscape of carbon dioxide emissions, a key driver of global environmental changes.

Whereas it is universally accepted that the automobile industry plays a major role in CO2 emissions, the current literature including (Jing et al. 2022), (Solaymani 2022), and (Ye et al. 2022) tends to use broad proxies like transport sector GDP, fuel consumption, or public transport development. These indicators, though informative, often obscure the industrial, as well as production-side, dynamics of motorization especially in emerging economies. The value added by this research is not to reiterate that vehicles generate emissions, but rather the extent to which vehicle production (here an upstream proxy of land transportation activity) is associated with CO2 emission in the ASEAN region. Contrary to developed economies, the member states of the ASEAN are undergoing a high rate of urbanization and industrialization and the increase in domestic vehicle manufacturing is both an emissions source and an indication of macroeconomic change. This study offers a more accurate and dynamic estimation of how the environment is pressured by transportation by incorporating the production of vehicles into the environmental assessment. Also, this method is highly policy-relevant: to the extent that the nexus of production and emissions can be known, cleaner manufacturing policies, industrial policy, and sustainable transport planning can benefit, something that the conventional proxies do not reflect. With transportation becoming a necessity in the world, it is important to explore how the production of vehicles determines emission paths to create effective mitigation measures to implement in the fast motorizing nations. Although current research has provided important insights into the linkage between transportation and CO_2 emissions, a deeper and more thorough understanding is still needed. This study can provide a more holistic perspective by incorporating vehicle production as a determinant of land transportation's influence on CO_2 emissions. The absence of previous studies exploring vehicle production as a proxy for land transportation's impact on CO_2 emissions underscores the novelty and significance of this research. By addressing this gap, the study can contribute unique insights that expand the existing body of knowledge. Hence, based on previous studies, it raises the question: how does land transportation, specifically the production of vehicles, impact CO_2 emissions, and what is the nature of this linkage? This study aims to investigate the impact of the automobile industry on carbon dioxide (CO_2) emissions in major vehicle-producing ASEAN countries, focusing on the role of economic growth, foreign direct investment, population growth, and vehicle production. It aligns closely with Sustainable Development Goal (SDG) 13, which calls for urgent action to combat climate change and its impacts. Understanding the environmental costs associated with industrial and transportation activities is essential for shaping sustainable development pathways and achieving global climate targets.

This study was motivated by the urgent need to solve the economic and environmental issues raised by CO_2 emissions related to land transportation in Malaysia. Like other nations, Malaysia heavily relies on land transportation as a pivotal driver of its economic development. However, this industry produces a large amount of CO_2 emissions despite making a major contribution to the nation's GDP. The outcomes of the research can have a direct bearing on the policies formulation and decision-making in the arena of transportation and environmental management in ASEAN. In the event that a meaningful connection between the production and emission of CO2 is found in vehicles, the policymakers are in a better position to rigorously shape the interventions to reduce emissions. Since the world is moving toward sustainable transport and reduction of emissions, a study on the context of ASEAN can provide regional insights that can be directly applied in the case of member states to meet their environmental goals. The results of the study can be used to make informed decisions in future in the urban and transportation planning to determine the contribution of vehicle production toward CO2 emission, and hence guide the incorporation of sustainable transportation practices, a factor that can ultimately help in developing regions that are more environmentally friendly.

This study advances methodological approaches in environmental research by using car production as a unique proxy for the impact of land transportation on CO_2 emissions. This methodological innovation could inspire further investigations using alternative proxies in other contexts. Besides, this study employs the panel autoregressive distributed lag (panel ARDL) model as opposed to the common linear ARDL method. The choice of this methodological approach is because the relationship between land transportation systems and CO_2 emissions may vary across different countries or regions, and panel ARDL can effectively capture both the short-run and long-run dynamics while accounting for heterogeneity across cross-sectional units**.** The panel ARDL approach is particularly well-suited for datasets that are a mixture of stationary and non-stationary variables (I(0) and I(1)), allowing for robust estimation of long-term equilibrium relationships and dynamic adjustments. Employing advanced econometric techniques like the panel ARDL method showcases the study's methodological sophistication, and using cutting-edge methodologies strengthens our analysis and enriches methodological diversity in the field.

Therefore, the unique contribution of this study is threefold. First, it not only contributes to the literature but also introduces a novel approach by using vehicle production as a proxy to assess the impact of land transportation on CO_2 emissions. This perspective allows for a more comprehensive understanding of the linkage between transportation and emissions. Second, this study is directly aligned with the United Nations' Sustainable Development Goal (SDG) 13, which calls for urgent action to combat climate change and its impacts. SDG 13 emphasizes the reduction of carbon emissions as a critical component of global efforts to limit temperature rise and mitigate climate change. By investigating the relationship between vehicle production and CO_2 emissions in ASEAN, this study contributes to the broader understanding of how land transportation can impact environmental sustainability, supporting efforts to achieve the SDG 13 targets for reducing greenhouse gas emissions. Finally, the study emphasizes the advantages of adopting the **p**anel ARDL method, as it effectively captures both the short-run and long-run dynamics between land transportation and CO_2 emissions across different countries or regions. This approach allows for heterogeneity among cross-sectional units and accommodates variables with different integration orders (I(0) and I(1)), providing a more robust and comprehensive analysis. The use of cutting-edge methodologies enhances the credibility of the analysis and contributes to methodological diversity within the field.

An overview of the automobile industry in ASEAN

The automobile industry is a significant and profitable sector globally, including in the ASEAN region. According to the ASEAN Automotive Federation's 2015 report, several ASEAN countries, such as Malaysia, Indonesia, the Philippines, Thailand, and Vietnam, are key vehicle producers. In an attempt to give a balanced insight into the automotive development of the region, this section will give a brief description of each of the major automotive-manufacturing countries of the ASEAN region without laying special emphasis on any particular country case. Following the government's adoption of a policy promoting import substitution industrialization (ISI) that restricted the import of finalized industrial goods, including completely built-up (CBU) units, the automobile industry in ASEAN got its start in the Philippines in the 1950s. The assembly industry prospered during the 1950s and 1960s, first shielded by import controls and then by high tariff barriers. Despite being the leading auto industry in Southeast Asia during the 1960s, the Philippines' position declined to fourth place by the turn of the millennium.

Malaysia's role in the regional automotive landscape emerged alongside other ASEAN economies rather than as an isolated case. The genesis of Malaysia's automobile industry can be traced back to the post-independence era when European manufacturers commenced production in the 1960s, closely followed by Japanese companies. A pivotal moment came in 1983 with the birth of Malaysia's national car brand, PROTON, a result of a joint venture between the Malaysian government and Japanese companies. HICOM spearheaded this venture by investing 70% of the RM150 million capital, while Mitsubishi Corporation and Mitsubishi Motors contributed the remaining 30%. A pivotal point in Malaysia's automotive history was reached in 1985 with the introduction of the Proton SAGA, the country's first automobile. With the founding of Perusahaan Otomobil Kedua Sdn. Bhd. (Perodua) in 1993, the sector continued to flourish. Over the years, both PROTON and PERODUA have flourished, becoming household names and driving the substantial growth of automobile production in Malaysia.

However, like other ASEAN countries, Malaysia's automotive expansion has been shaped by regional trade dynamics, foreign investment, and industrial policy.

The automobile industry in Indonesia has experienced remarkable growth since its inception in the 1960s, driven by government policies aimed at fostering domestic vehicle assembly and production. Initially modest in scale, the industry saw significant expansion through local joint ventures and strategic partnerships. Japanese automotive giants such as Toyota, Honda, and Mitsubishi have been pivotal in this transformation, establishing extensive manufacturing operations that have greatly contributed to Indonesia's status as the largest automotive market in Southeast Asia. Indonesia's large and growing population has been a key factor in this growth, which has created substantial domestic demand for automobiles. Among the world's most populous nations, Indonesia boasts a burgeoning middle class with increasing purchasing power, further fueling the demand for personal and commercial vehicles. The government's investment-friendly climate and strategic policies have attracted global manufacturers, making Indonesia a vital hub for automotive production and export in the region. Consequently, the Indonesian automobile industry meets the rising domestic demand and plays a crucial role in the global automotive supply chain, underscoring its significance in the international market.

Vietnam's foray into automobile production began with Mekong Auto in 1991 under the transformative "Doi Moi" policy, which emphasized local joint ventures with international manufacturers. The sector has since experienced a meteoric rise, particularly with the establishment of local manufacturers like VinFast, which have significantly accelerated industry growth. VinFast's ambitious plans to produce and export electric vehicles symbolize Vietnam's bold entry into the global automotive market. This rapid expansion and innovation underscore Vietnam's burgeoning potential as a formidable regional and international automotive arena player.

The automotive landscape in Thailand mirrors that of Indonesia in several remarkable ways, particularly in the emphasis on strategic joint ventures between local companies and international conglomerates. This synergy has driven Thailand's ascension as a premier automotive hub in Southeast Asia. The Thai government, recognizing the immense potential of these collaborations, has implemented a plethora of progressive policies to attract foreign investment and foster industrial growth. Thailand's automotive sector, much like Indonesia's, began with humble origins but has rapidly evolved into a powerhouse of production and innovation. The country has welcomed automotive giants such as Toyota, Honda, and Mitsubishi, whose partnerships with local firms have catalyzed a dynamic and resilient industry. These alliances have facilitated the transfer of advanced technologies and expertise and significantly bolstered Thailand's manufacturing capabilities. Moreover, the Thai automotive industry is characterized by a robust supply chain that includes vehicle assembly, parts manufacturing, and extensive research and development activities. This comprehensive ecosystem is further supported by Thailand's strategic geographical location, skilled labor force, and well-developed infrastructure, all of which contribute to its attractiveness as a destination for automotive investment. Figure 1 highlights the upward trend in vehicle production across ASEAN countries collectively, rather than emphasizing any single nation.

In summary, the automobile industries in ASEAN countries share roots in government policies and foreign partnerships but have developed in distinct ways. Thailand and Indonesia lead the region as major automotive hubs supported by strong joint ventures and domestic demand. Malaysia stands apart with its national brands PROTON and PERODUA, while Vietnam is rapidly emerging through innovation and electric vehicle production. The Philippines, once an early leader, has declined in competitiveness, highlighting both shared growth trends and divergent national trajectories.

Literature review

The model deemed most suitable for this study is the IPAT model, chosen based on various reasons and approaches employed by previous researchers. For instance, in an investigation conducted by (Di et al. 2011), the dynamics of energy demand and CO_2 emissions in China were assessed utilizing the IPAT model, encompassing factors related to the environment, population, technology, and economic expansion, the researchers uncovered pivotal insights into the drivers of environmental change and pollution in the nation. Their thorough analysis revealed a crucial finding: economic expansion emerged as the primary catalyst behind the surge in carbon emissions, playing a pivotal role in exacerbating pollution levels. This observation underscores the profound influence of economic development on environmental challenges and emphasizes the necessity for strategic policies to harmonize economic progress with environmental sustainability. Prior to (Di et al. 2011), (Feng et al. 2009) explored the lifestyle, technology, and CO_2 emissions in China, adopting the IPAT model. They discovered that heavy infrastructure development directly increased CO_2 emissions from 1949 to 2002. The IPAT model was also employed by (Shaari et al. 2021) to examine the environmental impact in Malaysia. The study's findings supported the idea that environmental degradation is determined by population growth, economic expansion, and technology development. This early research laid the groundwork for understanding the

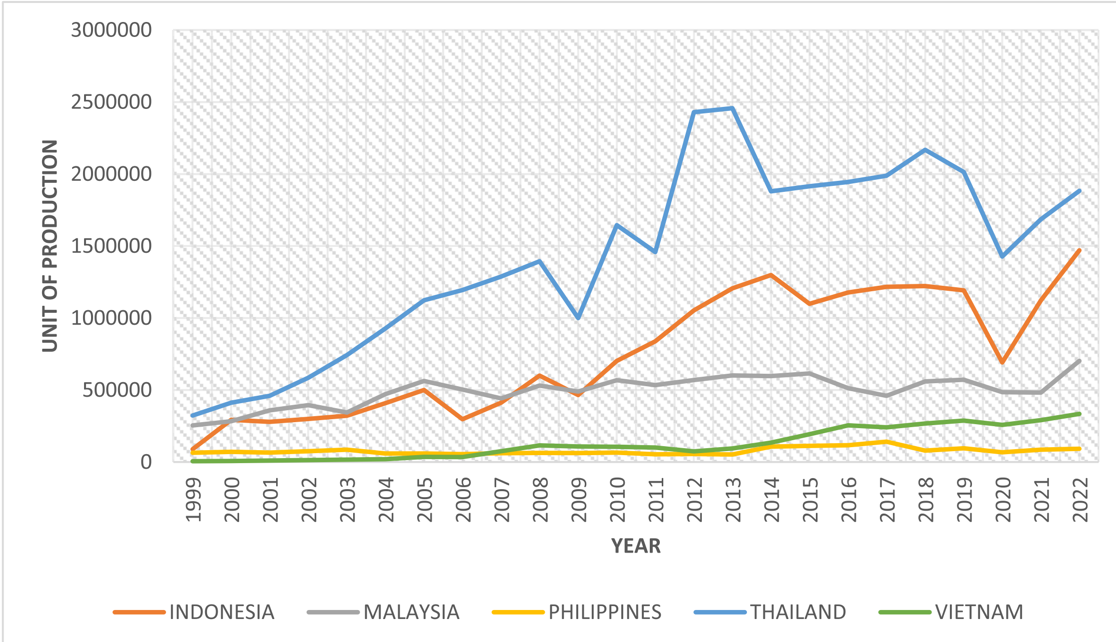


Fig. 1 Total annual vehicle production. Source: ASEAN Automotive Federation (2024)

intricate linkage between economic development, technology, and environmental impact.

Building upon these studies, (Chontanawat 2018) conducted a panel data study among ASEAN countries, confirming that emissions of CO_2 are largely contributed to by populations, fossil fuel usage, and energy consumption between 1971 and 2013. These findings highlight crucial trends, indicating that emissions are predominantly influenced by population growth and the simultaneous increase in per capita income. The firm establishment of fossil fuels as the primary energy source poses a significant challenge to any attempts at reversal. While advancements in energy efficiency contribute to emission reduction, changes in the carbon intensity of fossil fuels have limited impact, underscoring the complexity of addressing these interconnected environmental issues.

The latter relationships have been further put into perspective in the context of more recent ASEAN-based studies. As an example, Saboori and Sulaiman (Nguyen and Le 2020) analyzed the environmental Kuznets curve (EKC) in Malaysia and discovered that the increase in income levels and the rapid process of motorization become the major contributors of transport-related CO_2 emissions. Meanwhile, Hossain (Osobajo et al. 2020) considered ASEAN-4 (Thailand, Malaysia, Indonesia, and the Philippines) and proved that economic growth and energy-intensive industry, in particular, transport and manufacturing, are still the significant sources of emissions. On the same note, Nguyen and Le (Hossain 2012) have indicated that increasing vehicle numbers and industrial production in Vietnam have aggravated carbon emissions, particularly in urban corridors. This result supports the necessity of studying ASEAN as a unique regional bloc instead of generalizing the non-ASEAN situations.

Export activities are another contributing factor to CO_2 emissions, as they increase the demand for natural resources, leading to the generation of residues and waste (Putra and Oktora 2024). This result is evident in ASEAN countries such as Brunei, Malaysia, Myanmar, and Indonesia. The trend persists until export activities are diversified. The underlying reason is that the more specialized a country's exports are, the greater its reliance on natural resources. In BRICS countries, Malik and Sharma (Malik and Sharma 2024) found that technological innovations driven by private equity investment also contribute to carbon emissions. Similarly, Muhammad et al. (Muhammad et al. 2021) reported that foreign direct investment (FDI) leads to environmental degradation in developing and BRICS countries. Using annual data from 2002 to 2021, their study revealed that increased energy consumption results in higher CO_2 emissions. Private equity investments have targeted sectors such as wind energy, electric vehicles, and biofuels.

Environmental implications associated with FDI have also been pointed out in the ASEAN platform. As an example, Al-Mulali et al. (Saboori and Sulaiman 2016) discovered that in Indonesia, Thailand, and Malaysia, FDI inflows were linked to increased CO2 emissions because of the industrial growth. On the same note, Tang and Tan (Al-Mulali et al.

2015) demonstrated that manufacturing operations associated with export-oriented automotive companies in Malaysia have aggravated environmental stresses. These findings underscore the fact that the integration of ASEAN into the global production networks, especially in transportation manufacturing have different ecological implications.

In heavily industrialized countries like China, studies have shown that carbon emissions decreased by 9 percent with the increased use of renewable energy in electric vehicle production. However, the battery manufacturing process for electric cars demands significant materials and resource consumption, which presents environmental challenges (Guo et al. 2025). Reducing the environmental impact of battery production requires eco-friendly materials, advanced recycling technologies, and greater use of renewable energy. The rapid growth of China's automotive industry has also indirectly stimulated other sectors, such as steel, rubber, plastic, and other raw materials, which in turn exert additional pressure on the environment (Liu et al. 2013; Lin 2023).

(Santos 2017) undertook a conceptual study examining Europe's environmental landscape from 1990 to 2012. The study revealed a noteworthy 18% increase in greenhouse gas (GHG) emissions during this period, with a particularly concerning 14% surge in GHG emissions originating from the transport sector. This emphasizes the urgent need for sustainable transportation and emissions reduction strategies in response to escalating environmental threats. In a panel data study spanning thirty Chinese administrative regions from 2009 to 2017, (Zhang et al. 2020) delved into the intricate linkage between economic expansion, especially within the manufacturing industry, and increased pollutant emissions. The substantial influx of Foreign Direct Investment (FDI) into manufacturing, including the automotive sector, played a significant role in this connection. This research emphasizes the significance of maintaining equilibrium in economic expansion with environmental considerations and highlights the necessity of effective policies to address the environmental impact of industrial expansion.

(Ferrão and Amaral 2006) conducted a literature review on recycling activities related to vehicle parts within the European Union. Their investigation unveiled a substantial environmental burden resulting from material flux, with vehicle composition primarily comprised of various materials such as ferrous materials (71%), plastic (8%), glass (3%), fluids (2%), rubber (5%), nonferrous materials (7%), and miscellaneous components (4%). These findings underscore the environmental challenges posed by the automotive industry's material composition and emphasize the need for sustainable vehicle manufacturing and recycling practices. In a study conducted in Japan, Sato et al. (Ahmed et al. 2020) identified the significant role of energy consumption within the production chain, accounting for 22% of the overall energy consumed. This finding underscores the direct link between increased energy usage and heightened CO_2 emissions, emphasizing the urgent need for energy-efficient production processes and mitigating CO_2 emissions due to their substantial environmental impact.

Harun et al. 2025 conducted a survey involving 58 respondents and a comprehensive review of existing literature on end-of-life vehicle (ELV) legislation implemented in neighboring nations. The survey results were meticulously evaluated using SPSS. The subsequent paper delves into presenting and discussing the study's findings. According to the report, there is strikingly limited public awareness and acceptance of implementing ELVs. Molla et al. (Sato et al. 2019) examined important factors and possible directions to evaluate the long-term viability of end-of-life vehicle (ELV) recycling using a Strengths–Weaknesses–Opportunity–Threat (SWOT) analysis. This thorough, bottom-up approach combines quantitative and qualitative data from secondary research. The results indicate that there are major obstacles to the social, economic, technological, and environmental sustainability of India's ELV recycling system. The SWOT analysis draws attention to issues like using antiquated technologies and lacking an appropriate framework. It also notes some encouraging points, such as the potential market size and chances for resource recovery in the ELV recycling industry. Majekodunmi et al. (Harun et al. 2021) expanded the investigation to include the role of green technology in assessing environmental impact, focusing on Malaysia. Employing the ARDL approach, their results demonstrated that population growth contributes to CO_2 emissions and that green technology, measured by renewable energy consumption, can mitigate them. Furthermore, the study revealed that exports and economic expansion can harm the environment.

Up to now, though, the automobile industry is hardly ever singled out as a source of emissions in the CO2-growth nexus in ASEAN-oriented science. Current studies have focused on the aggregation of transport emissions or energy, or FDI at a greater scale. (Ozturk and Al-Mulali 2015) (Bekhet et al. 2017) discovered that direct association between transportation energy consumption in southeast Asia and emissions is observed, but in their research, they did not take into consideration the production of vehicles as an industrial factor. Similarly, Bekhet, Latif, and Yasmin (Tang and Tan 2015) revealed that the transportation industry of Malaysia is a major source of CO2 emission, but the contribution of domestic automobile production was not directly analyzed. These loopholes enhance the necessity to examine the production of vehicles as an economic source of emission at the ASEAN bloc level.

Despite the growing body of literature examining environmental degradation and CO_2 emissions, much of the existing research remains either country-specific, focusing on nations like China, Malaysia, or India, or broadly covers industrial emissions without isolating the automobile sector. Moreover, only a limited subset of studies has empirically assessed how vehicle production, FDI-linked manufacturing clusters, and rising motorization trends jointly influence emissions in ASEAN economies. In the context of ASEAN nations, there is a noticeable lack of comprehensive studies addressing the specific environmental impact of the automotive industry as a regional bloc. The unique economic structures, regulatory frameworks, and industrial policies of ASEAN countries warrant a more targeted investigation to understand how automobile-related emissions differ across borders. By incorporating this industrial metric within a robust modeling framework, this study not only complements earlier findings but also provides more targeted evidence for policy design tailored to the manufacturing-intensive transport sectors in the region.

Methodology

The conceptual basis of this research is grounded in the well-established IPAT model, which posits that impact equals the product of population, affluence, and technology (IPAT = population × affluence × technology). This conceptual framework serves as a valuable cornerstone, offering insights into the intricate linkage between these factors and their collective impact on CO_2 emissions. The IPAT model delineates the influencing components into three distinct factors: population, affluence (representing economic expansion), and technology. Recognizing the limitations of the original deterministic IPAT model, Dietz and Rosa (Molla et al. 2023) introduced the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology), a stochastic reformulation that allows for empirical estimation and hypothesis testing. The STIRPAT model treats the IPAT identity as a flexible and testable stochastic equation, enabling a more nuanced analysis of environmental impacts. In line with this evolution, this study carefully selects variables within the IPAT framework, specifically focusing on indicators that capture demographic trends, economic growth, and technological advancements to better understand their individual and combined effects on CO_2 emissions. By adding a stochastic version to this model, Dietz and Rosa (Molla et al. 2023) expanded it and made it possible to estimate how population, wealth, and technology affect a country's CO_2 emissions.

$$I = f(P, A, T) \tag{1}$$

In this study, CO_2 emissions were employed as a stand-in for the environmental impact. The population can be represented by population growth, the population can be represented by GDP per capita, the population can be represented by foreign direct investment, and the total number of vehicles produced can be represented by technology. Population growth is considered a key component in the context of this inquiry, as it is linked to higher energy demand and consequently higher CO_2 emissions that come with a larger population. This aligns with the findings of Ahmed et al. (Majekodunmi et al. 2023b), who noted the same pattern in India. The idea that population increase could potentially result in adverse effects on the environment was reinforced by Zarco-Periñán et al. (Dietz and Rosa 1997), especially when it comes to Spanish cities. Osobajo et al. (Huang et al. 2021) take this idea even further by showing that there is a two-way relationship between population growth and CO_2 emissions. Not only does population pressure raise emissions, but environmental damage also makes urban stress and demographic growth worse. This feedback loop becomes clearer in the context of ASEAN-5, where rising urbanization and industrialization increase the use of resources. The effects are considerable because a growing population leads to more reliance on fossil fuels, more energy use, and long-term damage to the environment, which are variables that static estimating methods don't always take into account. So, to understand how population increase affects things, we need models that show how things change over time and how different regions are. This study looks at these models using multiple panel estimators.

H_1: There is a positive linkage between population growth and CO_2 emissions.

Economic expansion or affluence of a country is found to have a direct impact on transportation and industrial operations, which in turn affect CO_2 emissions. Many studies have demonstrated the negative effects of economic expansion on CO_2 emissions, including those conducted in Malaysia by Raihan et al. (Ahmed et al. 2023), Indonesia by (Zarco-Periñán et al. 2021), China by Zhao et al. (Raihan et al. 2023), and the European Union by Onofrei et al. (Pujiati et al. 2023). Studies conducted on certain areas, such as the top emitters of CO_2, Bangladesh, and the ASEAN region, provide strong evidence for the link between increasing economic expansion and environmental deterioration, which is mostly caused by rising energy consumption.

H_1: There is a positive linkage between economic expansion and CO_2 emissions.

Finally, technology emerges as a critical factor in determining the carbon intensity of economic activities. Advanced and cleaner technologies are shown to lead to more efficient resource use and reduced emissions, as Razaq et al. (Zhao et al. 2022) highlighted in their focus on the BRICS nations. The study showed that progress in green technology contributes to environmental preservation, while outdated technologies may increase emissions. Similarly, Ahmed et al. (Onofrei et al. 2022) and Saidi and Omri (Razzaq et al. 2021) emphasized the effectiveness of adopting renewable energy in alleviating environmental impact within both BICS and OECD countries.

H_1: There is a positive linkage between technology and CO_2 emissions.

Applying the IPAT model to this study, the researchers can analyze how population size, economic expansion, and technological advancements influence CO_2 emissions in ASEAN5 countries land transportation sector. By examining these factors individually and in conjunction, the study can comprehensively understand their relative contributions to emissions. Furthermore, the IPAT model also emphasizes the interconnectedness of these factors. For instance, as economic expansion (affluence) leads to increased income and consumption patterns, it can drive up the demand for vehicles and transportation services, thereby affecting CO_2 emissions. Technological advancements can influence economic expansion and emissions by determining resource use efficiency. Utilizing the IPAT model as a foundational framework, this study can identify which specific elements—population growth, economic affluence, or technological progress—dominate CO_2 emissions in the ASEAN5 countries' land transportation sector.

Data

The data used in this study includes the following key variables: **c**arbon dioxide emission (CO_2), measured in metric tons per capita, gross domestic product (GDP), measured in constant US dollars, foreign direct investment (FDI), measured in net inflows as a percentage of GDP, population growth (PG), measured as the annual growth rate of the total population, and total vehicle production (TVP), measured as the total number of vehicles produced annually. The variable selection in this study is based on the STIRPAT framework, which extends the IPAT model by linking environmental impact to population, affluence, and technology. CO_2 emissions are taken as the dependent variable to represent environmental pressure. Population growth (PG) reflects demographic influence, GDP measures affluence through economic activity, and foreign direct investment (FDI) captures globalization and technological transfer. Total vehicle production (TVP) is used as a proxy for technology and industrial activity, providing a direct measure of transportation-related emissions beyond conventional indicators. The empirical scope of the study encompasses the ASEAN5 countries, specifically Vietnam, the Philippines, Indonesia, Malaysia, and Thailand. These countries were selected because data for each relevant variable were available for the entire study period, spanning from 1999 to 2022. All the data were extracted from reliable sources, including the World Bank. The model used to analyze these impacts is specified as follows:

$$CO_2 = \int \left(GDP_{it}, FDI_{it}, PG_{it}, TVP_{it} \right) \tag{2}$$

Subsequently, we have applied a natural logarithm transformation to all variables to mitigate heteroscedasticity. Moreover, this conversion enables the estimated coefficients of the variables to directly reflect elasticities. Consequently, model (2) can be re-expressed as follows:

$$\begin{aligned} LNCO_2 = & \alpha + \beta_1 LNGDP_{it} + \beta_2 LNFDI_{it} \\ & + \beta_3 LNPG_{it} + \beta_4 LNTVP_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

In Eq. (3), $LNCO_2$, LNGDP, LNFDI, LNPG, LNTV, and ε_{it} represent the CO_2 emission, gross domestic product, foreign direct investment, population growth, total vehicle production, and the error term, respectively. The parameter of β_1, β_2, β_3 and β_4 represent the long-run elasticities of CO_2 with respect to foreign direct investment, gross domestic product per capita, population growth, and total vehicle production, respectively. The subscripts i and t in the equations denote the country and time.

Estimation procedure

Panel data, which include cross-sectional and time-series data, are used in this study. Compared to only time-series or cross-sectional analyses, panel data analysis has the following benefits: In comparison to pure time series or cross-sectional data, it: (i) yields more reliable parameter estimates; (ii) allows for the control of unobservable factors that change over time or across units; (iii) reduces estimation bias that can result from combining groups into a single time series; (iv) enables the modeling of both individual and common group behaviors; and (v) encompasses more information, variability, and efficiency.

Cross-sectional dependence (CSD) test

Prior to panel data analysis, it is imperative to do a cross-sectional dependence test (CSD test) [Pesaran, (Saidi and Omri 2020)]. In cross-country panels, geographical effects, spillovers, or unobserved common factors can cause cross-sectional dependence (CSD) (Pesaran et al. 2001; Andrews 2005). Although it is frequently believed that error terms in cross-country panels are cross-sectionally independent, panel data models have been shown to contain CSD. Estimates may contain inconsistent errors if CSD is ignored during the estimation process(Pesaran et al. 2001). The following is the equation for Pesaran's CSD test.

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \rho^{ij} \right) \rightarrow N(0,1) \tag{4}$$

Pesaran's CSD statistic tests the null hypothesis of no cross-sectional dependence. When the number of cross sections (N) approaches infinity and the periods (T) are sufficiently large, the test statistic follows a two-tailed standard normal distribution, N (0, 1).

Panel unit root tests

Before performing panel cointegration analysis, it is crucial to evaluate the stationarity and determine the integration order of the variables in the panel series. Stationarity refers to the condition where the statistical properties of a time series, such as mean, variance, and autocorrelation, remain constant over time. This means the series exhibits no trends, periodic fluctuations, or shifts in variance, ensuring consistency for reliable statistical modeling. To assess the stationarity of variables, panel unit root tests are typically employed, as they help detect whether individual series or the entire panel maintains constant statistical properties. Maddala and Wu (Chudik and Pesaran 2013) propose four primary panel unit root tests: the Levin–Lin–Chu test, Im–Pesaran–Shin test, Augmented Dickey–Fuller (ADF) test, and Phillips–Perron test, each of which offers options for models with only an intercept or both trend and intercept.

These panel unit root tests are vital because non-stationary series can produce misleading or spurious results, potentially distorting further analysis, such as cointegration tests. The Levin–Lin–Chu and Im–Pesaran–Shin tests, along with Fisher-type panel unit root tests, share a general framework, allowing flexibility depending on the data structure. By conducting these tests, researchers can better understand the degree of integration of the variables, ensuring the appropriate application of models like cointegration techniques. In doing so, panel unit root testing plays a crucial role in verifying the reliability of the variables for further statistical analysis.

$$\Delta Y_{it} = \left(\rho_i - 1\right)\gamma Y_{it-1} + \sum_{j=1}^{Pi} \gamma_{ij}\Delta Y_{it-j} + \delta_{mi}d_{mt} + V_{it}, m = 1, 2, 3 \tag{5}$$

The term *dmt* refers to the deterministic component of the model, and the variable Y has a unit root for individual i when $\rho = 0$, implying that Y is non-stationary. On the other hand, if ρ is less than zero, Y becomes stationary around this deterministic part. The Levin–Lin–(Chao) test is a pooled Augmented Dickey–Fuller (ADF) test, used to determine whether panel data is stationary. The null hypothesis ($H0$) asserts that all cross sections are non-stationary, meaning $\gamma = 0$, while the alternative hypothesis ($H1$) suggests stationarity across all cross sections, indicating $\gamma < 0$. The test evaluates γ using a t-statistic, which, under large-sample conditions where both the number of individuals (I) and periods (T) approach infinity, follows an asymptotic normal distribution. The Levin–Lin–(Chao) test assumes that all cross sections are homogeneous, but it tends to lose statistical power when the time dimension (T) is small or in cases where a fixed effects model is used. Additionally, the test does not account for cross-sectional correlation unless specific adjustments for cross-sectional effects are made. Similar pooled ADF tests include those developed by Im, Pesaran, and Shin, as well as Fisher-type tests.

In discussing the Levin–Lin–(Chao) test, it is important to note that while it is widely used to check for stationarity in panel data, its reliance on homogeneity assumptions across cross sections and limitations with small T reduce its effectiveness in some cases. These limitations make the test less reliable when handling heterogeneous panels or when cross-sectional dependencies exist unless modifications are applied to account for these factors. Alternative pooled ADF tests, such as those by Im, Pesaran, and Shin, or Fisher, offer similar functionality but may address some of these limitations depending on the context. For both tests, the hypotheses are:

H_0: $\gamma = 0$ (for all i)
H_1: $\gamma < 0$ (for at least one i

In the case of the Im, Pesaran, and Shin tests, it is necessary to conduct an ADF test for each cross section individually. The t-tests for γ from each cross section take the following form:

$$\underline{t} = \frac{1}{N}\sum_{i-1}^{N} t_i \sim N(0,1) ifT \rightarrow \infty followedbyN \rightarrow \infty \tag{6}$$

It is important to recognize that T and Pi can differ across individual i, leading to different critical values for each combination of T and Pi. In the Fisher-type test, the ADF test is applied separately to each cross section, and the p-values from the individual unit root tests for each cross section are used in the overall analysis. The equation for the Fisher-type test is formulated as follows:

$$P = -2\frac{1}{N}\sum_{i-1}^{N} lnln\left(P_i\right) \sim X^2 2NwhenT \rightarrow \infty \tag{7}$$

The test follows an asymptotic chi-square distribution with 2N degrees of freedom. A significant advantage of employing the Fisher-type test is its capability to accommodate unbalanced panels. Moreover, it permits varying lag lengths for individual ADF tests. However, a drawback of this test is that p-values derived from Monte Carlo simulations are often used.

Panel cointegration tests

Cointegration refers to the presence of long-term or multiple long-term linkages between two or more non-stationary time series variables. Researchers use cointegration tests to determine whether these non-stationary time series exhibit a stable, long-term equilibrium linkage. In this study, Pedroni (Maddala and Wu 1999) and Kao (Pedroni 1999) panel cointegration tests were employed to identify long-term associations among variables in the panel series. Both tests start with the null hypothesis that no cointegration exists among the variables. For example, Pedroni (Maddala and Wu 1999) examines long-term linkages using a specific cointegrating equation to detect any stable linkages.

Cointegration is particularly important in time series analysis because even when variables are individually non-stationary, they may still maintain a stable long-term linkage. These tests help identify such equilibrium connections, especially in cases where short-term fluctuations mask the underlying trends. In the context of panel data analysis, the Pedroni and Kao tests provide a robust methodology to explore these long-term linkages. Rejecting the null hypothesis of no cointegration suggests that the variables move together over time, which is critical for understanding economic, financial, or policy-related variables that share a common path, such as exchange rates, GDP, or interest rates. Pedroni (Maddala and Wu 1999), for instance, investigates the long-term association using the following cointegrating equation:

$$y_{it} = \alpha_i + \delta_{it} + \beta_i x_{it} + \varepsilon_{it} \tag{8}$$

In the equation, t = 1,…, T. T represents the observations, and i = 1,…, N. N is the number of panel members. Panel cointegration tests use seven test statistics to assess the null hypothesis that there is no cointegration. Of these, three (group rho-statistic, group PP-statistic, and group ADF-statistic) use 'between-dimension' (group) statistics, while four (v-statistic, rho-statistic, PP-statistic, and ADF-statistic) are based on 'within-dimension' statistics. The estimated residuals obtained from the cointegrating equation are used for all tests. When the panel series' time dimension is constrained, the Kao panel cointegration test performs better than the Pedroni cointegration test (Kao 1999). According to Kao (Pedroni 1999), the Kao panel cointegration test presumes that the slope coefficients of each panel series member are uniform.

Panel cointegration estimates—the long-run effects

This study examines the long-term impacts of GDP, foreign direct investment, population growth, and total vehicle production on CO_2 emissions using the estimation techniques of Pooled Mean Group (PMG), Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS). Due to probable endogeneity and autocorrelation, standard pooled least squares estimates may yield skewed results when variables in a panel series are cointegrated over an extended period. In the setting of cointegrated variables, both DOLS and FMOLS are helpful in overcoming these issues and offering more dependable estimates.

The application of DOLS and FMOLS helps correct issues like autocorrelation and endogeneity by incorporating dynamics that better capture long-term linkages. This is particularly important in studies dealing with environmental impacts, where multiple economic and social factors interact. By using these advanced techniques, researchers can more accurately analyze the connections between economic expansion, industrial activities, and environmental outcomes, offering insights that are critical for designing effective policies to reduce CO_2 emissions and promote sustainable development. The Panel DOLS estimation method is a parametric approach that incorporates both current and lagged values of the variables. To estimate the cointegration vector, DOLS employs the following model:

$$y_{it} = \alpha_i + \beta_i x_{it} + \sum_{k=-Ki}^{Ki} \gamma_{ik} \Delta x_{it-k} + \varepsilon_{it} \tag{9}$$

where K_i and $-K_i$ represent lags and leads, respectively.

The panel FMOLS method is a nonparametric technique. The panel FMOLS estimator can be computed using the following panel regression model:

$$\hat{B} * GFM = N^{-1} \sum_{i=1}^{N} \hat{B} * FM, i \tag{10}$$

where $\hat{B} * FM, i$ denotes the standard FMOLS estimator applied to the ith member of the panel.

The selection of the Panel ARDL model also reflects its ability to handle mixed order integration (I(0)/I(1)) and cross-sectional heterogeneity, which are present in our dataset, further supporting its appropriateness for this study.

Results

Table 1 presents the descriptive statistics for all the variables, particularly $LNCO_2$, LNPG, PNTVP, LNGDP and LNFDI. The mean values indicate that, on average, $LNCO_2$ is 0.836, LNPG is 0.149, LNTVP is 12.575, LNGDP is 26.418, and LNFDI is 1.195. The median values are close to the means, suggesting a roughly symmetrical distribution for most variables, except LNPG and LNFDI. The range of values, highlighted by the minimum and maximum statistics,

Table 1 Descriptive statistics

	LNCO2	LNFDI	LNGDP	LNPG	LNTVP
Mean	0.8362	1.1945	26.4178	0.1486	12.5750
Median	0.7415	1.3147	26.4343	0.2108	12.9037
Maximum	2.1078	2.3668	27.7464	0.9568	14.7145
Minimum	− 0.4463	− 1.3237	25.1958	− 2.0101	8.6167
Std. Dev	0.7229	0.6069	0.5681	0.5375	1.3709
Skewness	0.1683	− 1.6596	0.2929	− 1.3216	− 0.5916
Kurtosis	1.8713	6.9964	2.8159	5.8313	2.8172

Table 2 Residual cross-section dependence results

Test	Null hypothesis	Statistic	Prob
Pesaran CD	No cross-section dependence	0.086743	0.9309

shows significant variability, especially for LNPG and LNFDI, which have the largest spreads. The standard deviations confirm this variability, with LNPG and LNFDI having higher dispersion compared to other variables. Skewness values indicate that LNPG and LNFDI are notably skewed to the left, while LNTVP is slightly skewed to the left and LNGDP and LNCO2 are slightly skewed to the right. The kurtosis values suggest that LNPG and LNFDI have heavy tails, indicative of more extreme values compared to a normal distribution, whereas the other variables have kurtosis values closer to 3, suggesting distributions closer to normality. These statistics provide an overview of the central tendency, dispersion, and shape of the distribution of the variables, highlighting the differences in their distributions and potential implications for further analysis.

According to the Pesaran CD test statistic and related p-value, there is no significant cross-section dependence among the residuals in the panel data. This supports the residual cross-section dependence test results presented in Table 2. This result validates the assumption of cross-sectional independence in the analysis and has significant consequences for the selection of econometric models. The Pesaran CD test shows that cross-sectional dependence is not statistically significant ($p = 0.9309$), but the Panel ARDL model is still a good choice. This choice isn't just based on the fact that there is cross-sectional dependence; it's also based on how well the Panel ARDL captures dynamic heterogeneity, mixed integration orders (I(0)/I(1)), and short-run versus long-run asymmetries across the ASEAN-5 economies. These traits are very essential because the countries in the sample have different structures, policies, and levels of development. Also, even when CSD is not statistically present, it may be too limiting in applied study to completely ignore any interdependencies. So, Panel ARDL makes it easier to capture intricate interactions between the environment and the economy, which is why it was used in this study even though there wasn't much evidence of CSD.

Table 3 Panel unit root results

	ADF			PP	
	Variables	Statistic	Prob	Statistic	Prob
Level	LNCO2	7.2730	0.6994	6.2692	0.7922
	LNFDI	35.0313	0.0001	50.9560	0.0000
	LNGDP	6.4203	0.7788	16.2540	0.0926
	LNPG	0.4689	1.0000	1.3761	0.9993
	LNTVP	16.0001	0.0996	25.5527	0.0044
First Difference	LNCO2	41.6161	0.0000	77.6634	0.0000
	LNFDI	69.7548	0.0000	255.8600	0.0000
	LNGDP	45.6502	0.0000	52.5424	0.0000
	LNPG	24.2491	0.0070	19.3927	0.0355
	LNTVP	43.7998	0.0000	106.2370	0.0000

Table 4 Kao residual cointegration test

	Null Hypothesis	t-Statistic	Prob
ADF	No cointegration	− 2.09983	0.0179

Table 3 presents the panel unit root test results using both the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests, selected for their robustness in handling cross-sectional dependence and heteroskedasticity in panel data. At the level, the results indicate that LNC02 and LNPG are non-stationary, with high *p*-values (e.g., 0.6994 for LNC02 in ADF) failing to reject the null hypothesis of a unit root. Conversely, LNTPV and LNPDI show evidence of stationarity at the level, indicated by significant *p*-values (e.g., 0.0001 in ADF and 0.0000 in PP for LNPDI). Upon taking the first differences, all variables become stationary, as indicated by highly significant *p*-values (e.g., 0.0000 for LNC02, LNGDP, LNPDI, LNPG, and LNTPV). This suggests that the series are integrated of order one, I(1), which justifies proceeding with the Panel ARDL analysis.

The results of the Kao Residual Cointegration Test, as presented in Table 4, reveal a significant finding regarding the linkage among the variables in the panel data. The null hypothesis of no cointegration is tested using the Augmented Dickey–Fuller (ADF) methodology, yielding a t-statistic of 2.09983 and a probability value of 0.0179. The highly negative t-statistic, coupled with the p-value significantly below common significance levels (e.g., 0.01 or 0.05), provides strong evidence to reject the null hypothesis. This rejection indicates that the variables in the dataset are cointegrated, meaning they share a long-term equilibrium linkage (Table 5).

Table 5 presents the panel cointegration test results using both the Trace and Maximum Eigenvalue tests. The results

Table 5 Panel cointegration results

No. of CE(s)	Trace test	Prob	Max-Eigen test	Prob
None*	120.7000	0.0000	73.9000*	0.0000
At most 1*	58.4800	0.0000	37.2400*	0.0001
At most 2*	30.2200	0.0008	22.9100*	0.0111
At most 3	16.7700	0.0796	15.2700	0.1224
At most 4	13.5500	0.1948	13.5500	0.1948

* represents significant at the 10% level

Table 6 Panel FMOLS and panel DOLS results

Variables	FMOLS	DOLS
LNFDI	−0.0259 (0.7838)	0.1252*** (0.0030)
LNGDP	0.4148*** (0.0000)	0.2413*** (0.0109)
LNPG	0.1383*** (0.0000)	0.0840 (0.3679)
LNTVP	0.2405*** (0.0000)	0.1996*** (0.0000)
R2	0.9861	0.9982

*** significant at 1% level

indicate strong evidence of cointegration among the variables LNCO2, LNPG, LNTVP, LNGDP, and LNFDI. The null hypothesis of no cointegration ("None") is rejected at the 0.0000 probability level for both tests, suggesting at least one cointegrating linkage exists. Additionally, the hypotheses of at most one and most two cointegrating equations are also rejected, with significant *p*-values (e.g., 0.0001 for "At most 1" in the Max-Eigen test and 0.0008 for "At most 2" in the Trace test), indicating multiple cointegrating vectors. However, the null hypotheses of at most three and most four cointegrating equations cannot be rejected, with *p*-values above common significance levels (e.g., 0.0796 for "At most 3" in the Trace test). These results collectively suggest that there are up to two cointegrating linkages among the variables, implying that they share long-term equilibrium linkages.

This study explores the link between CO_2 emissions and factors such as foreign direct investment (FDI), economic expansion, population growth, and the automobile industry, using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) methods. The FMOLS results, presented in Table 6, show that economic expansion is a significant determinant of CO_2 emissions, where a 1% rise in economic expansion results in a 0.4148% increase in emissions, significant at the 1% level. This magnitude suggests that rapid economic growth in ASEAN countries could substantially intensify environmental pressures, given their high reliance on energy-intensive industries and fossil fuels. Similarly, the automotive industry plays a notable role, with a coefficient of 0.2405, reflecting its significant contribution to emissions at the 1% level. However, FDI and population growth do not significantly affect CO_2 emissions in the FMOLS model.

The DOLS results show that FDI, with a coefficient of 0.1252, becomes a significant factor at the 1% level, contributing to higher CO_2 emissions. Economic expansion, with a slightly lower coefficient of 0.2413, remains a strong predictor at the 1% level, reinforcing its significant impact on emissions. In practical terms, this result means that continued economic development, if not accompanied by green initiatives, could further escalate emissions problems across ASEAN economies. The vehicle industry also demonstrates a notable influence on emissions, with a coefficient of 0.1996, significant at the 1% level, highlighting its key role in driving emissions. Population growth, however, continues to have a negligible effect. The DOLS model, with an R-squared of 0.9982, exhibits strong explanatory power, accounting for 99.82% of the variation in CO_2 emissions.

The robustness results from Table 7 using the Panel ARDL model provide important insights into the factors influencing CO_2 emissions. The analysis reveals that FDI has a significant positive impact on CO2 emissions, with a coefficient of 0.1365, indicating that a 1% increase in FDI leads to a 0.1365% rise in emissions. Population growth emerges as a critical driver, with a highly significant coefficient of 2.1431, showing that a 1% increase in population growth results in a substantial 2.1431% increase in CO_2 emissions. This result highlights the pressing need to manage population growth to mitigate environmental impacts. The total vehicle production also shows a significant positive effect on emissions, with a 1% increase in production associated with a 0.0954% rise in CO_2 emissions, significant at the 5% level. Interestingly, economic expansion does not significantly impact CO_2 emissions in this model, suggesting that its effect may be more complex and dependent on other factors or model specifications. These findings confirm the robustness of the significant linkages between FDI, population growth, production levels, and CO_2 emissions, emphasizing the multifaceted nature of the determinants of environmental degradation.

The Panel ARDL results reveal notable differences compared to the FMOLS and DOLS estimations, particularly

Table 7 Panel ARDL Results

Variables	LNFDI	LNGDP	LNPG	LNTVP
Coefficient value	0.1365*** (0.0030)	−0.1593 (0.4189)	2.1431*** (0.0021)	0.0954** (0.0386)

***,** significant at 1 and 5% level

regarding population growth and economic expansion. While FMOLS and DOLS models indicate that population growth is not a statistically significant driver of CO_2 emissions, the ARDL model shows that it is a highly significant and positive contributor. Conversely, economic expansion (LNGDP) is statistically significant in the FMOLS and DOLS models but becomes insignificant in the ARDL framework. These discrepancies likely stem from the ARDL model's dynamic nature, which captures both short- and long-run adjustments and accounts for country-specific heterogeneity and lag structures. The significance of population growth in ARDL may reflect its cumulative long-term influence, which static models like FMOLS and DOLS may underrepresent. Similarly, the insignificance of economic growth in the ARDL model might result from multicollinearity with other regressors over time or different lag responses among countries. These results highlight the importance of model selection and interpretation, especially when assessing complex, multi-dimensional drivers of environmental degradation.

Discussion

The findings obtained through the FMOLS and DOLS analyses provide valuable insights into the interplay between FDI inflows, economic expansion, population growth, vehicle production, and CO2 emissions across ASEAN-5 nations, namely Malaysia, Indonesia, Thailand, the Philippines, and Vietnam. The results indicate that FDI inflows can significantly impact environmental degradation. This is attributed to establishing industries and manufacturing facilities that often prioritize profit and productivity over sustainable practices. In the ASEAN context, FDI has historically been attracted to export-oriented, labor-intensive, and manufacturing-based economic structures, especially in automotive, electronics, and resource-processing sectors. FDI in ASEAN-5 has been intense in automotive-producing countries like Thailand and Indonesia where manufacturing clusters are developing to attract the Japanese and Korean companies. This type of industrial concentration raises the emissions of production processes and strengthens the reliance of regions on cars powered by combustion engines. These industries may focus on maximizing output and efficiency, often neglecting environmental considerations. Consequently, the emission levels rise, contributing to environmental degradation and exacerbating the adverse effects of climate change. The findings emphasize the importance of adopting sustainable practices within industries driven by FDI. Both foreign investors and domestic stakeholders must prioritize environmental sustainability alongside economic expansion. By integrating environmentally friendly technologies, promoting energy-efficient production processes, and adopting cleaner energy sources, the negative impacts of FDI on the environment can be mitigated.

Furthermore, policymakers should implement robust regulations and incentives to encourage responsible and sustainable practices among industries receiving FDI. This can include imposing emission reduction targets, promoting the use of renewable energy, and incentivizing the adoption of eco-friendly technologies. Given the cross-country context of ASEAN-5, a regional framework encouraging green FDI practices, backed by harmonized environmental standards and certification across member countries, should be developed to guide foreign investors toward sustainable operations. Such coordination is necessary because ASEAN economies share similar export-oriented structures, industrial supply chains, and competition for manufacturing investment. By aligning economic expansion with environmental sustainability, ASEAN-5 nations can strike a balance that fosters economic development while minimizing the ecological footprint. (Huang et al. 2021) support the finding with the utilization of distinct analytical approaches, including the Ordinary Least Squares (OLS), Fixed Effects (FE), and Random Effects (RE) models. However, it is worth noting that Demena and Afesorgbor(Gutierrez 2003) put forth a contrasting argument, suggesting that FDI can contribute to a decrease in environmental emissions. Huang et al. (Demena and Afesorgbor 2020) and the current study shares a similar stance, suggesting that FDI positively impacts environmental emissions. Despite the methodological differences, both studies align in highlighting the potential environmental consequences of FDI inflows. The consistency in findings across various analytical techniques enhances the robustness and reliability of the overall conclusion.

Furthermore, the findings of this study reveal a significant positive linkage between economic expansion and environmental degradation in the long run, supported by Osobajo et al. (Huang et al. 2021) who found that higher economic expansion can lead to environmental conservation at certain stages. This connection aligns with ASEAN-5's development trajectory, where economic growth has been driven largely by industrial production, manufacturing exports, energy-intensive infrastructure development, and rapid urbanization. The findings of this study reveal that economic expansion plays a complex dual role in influencing CO_2 emissions. In the short to medium term, higher economic growth increases industrial activities, energy consumption, and vehicle production, all of which contribute to greater CO_2 emissions. This positive relationship was confirmed by the FMOLS and DOLS results. However, as economies mature, economic growth can also create opportunities to mitigate environmental degradation. Greater income levels facilitate investments in cleaner technologies, the transition toward service-oriented industries with lower carbon footprints, and the implementation of stricter environmental regulations. Therefore, while economic growth initially drives up CO_2 emissions, it can also support a shift toward more sustainable and low-carbon development in the longer term. This trend is consistent with the structural transformation observed in ASEAN economies, where early-stage industrialization leads to higher emissions before gradual adoption of green technology and policy reforms. This pattern was observed consistently across ASEAN-5 countries, although the pace and magnitude of the transition varied depending on the country's stage of development. This highlights the importance of policies that encourage green innovation and environmental regulation alongside economic development.

Population growth has implications for environmental degradation, primarily due to the increased demand for energy. As the population expands, there is a corresponding rise in energy consumption for various purposes, such as residential electricity, transportation systems, and industrial production. ASEAN countries are experiencing rapid demographic expansion, urban migration, and growing middle-class consumption, all of which translate into higher per capita energy requirements and mobility demand. This heightened energy consumption has direct consequences on carbon emissions, leading to an exacerbation of climate change. The increased reliance on fossil fuels to meet the escalating energy needs further compounds the issue by introducing air and water pollution, thus intensifying environmental degradation. The study conducted by Osobajo et al. (Huang et al. 2021) delves deeper into this linkage between population growth and CO_2 emissions. Through the application of Granger causality analysis, they reveal that population growth not only influences CO_2 emissions but that CO2 emissions also impact population growth. This bidirectional linkage underscores the intricate dynamics between population dynamics and environmental outcomes. The implications of population growth on the environment are far-reaching. The strain on natural resources and ecosystems intensifies as the global population increases. In the ASEAN-5 context, rapid urbanization linked to population growth further stresses energy systems, necessitating coordinated regional efforts in urban planning and energy efficiency programs. This demonstrates how demographic trends interact with ASEAN's evolving urban-industrial structure, amplifying pressures on energy systems and environmental quality.

The findings of this study provide evidence that vehicle production has a significant impact on environmental degradation. This finding is similar to Jing et al. (Jing et al. 2022); however, their study focused on public transportation rather than vehicle production. The process of manufacturing vehicles involves various stages that contribute to environmental harm. The extraction and processing of raw materials for vehicle production can lead to habitat destruction, soil erosion, and water pollution. Mining activities for metals such as iron, aluminum, and copper require extensive land clearance, resulting in the destruction of ecosystems and the displacement of wildlife. Additionally, the extraction and refining of petroleum for fuel production can cause oil spills and contamination of water bodies, posing a threat to aquatic life and ecosystems. Besides, the production of vehicles requires substantial energy consumption, primarily derived from fossil fuels. Burning fossil fuels during manufacturing processes releases greenhouse gases and air pollutants, contributing to climate change and air pollution. These emissions have adverse effects on both human health and the environment, leading to respiratory problems, smog formation, and the degradation of air quality. This relationship is particularly relevant in ASEAN-5, where economic policies have supported domestic vehicle manufacturing as part of industrialization and trade strategies, leading to rising domestic fleets and dependence on combustion-engine technologies. These patterns were evident not only in Malaysia but consistently observed across other ASEAN-5 nations, highlighting a broader regional challenge in managing the environmental impacts of industrial vehicle production.

Our comprehensive study makes a significant contribution to the field of environmental science by unequivocally confirming the substantial and undeniable influence of land vehicles on environmental degradation across ASEAN-5 nations. Through the extensive data analysis and rigorous assessment conducted in this research, we have not only shed light on the critical role played by land vehicle emissions, including exhaust emissions, particulate matter, and greenhouse gases, in degrading the environmental quality of ASEAN ecosystems, but we have also quantified the extent of this impact. Given that ASEAN economies rely heavily on road-based logistics, automobile ownership, and manufacturing-led transport demand, these findings further reflect how economic structure intensifies emissions. Our findings offer actionable insights, emphasizing the urgency of implementing effective mitigation strategies and sustainable transportation policies across the ASEAN-5 bloc. By doing so, our study provides a vital foundation for policymakers, environmentalists, and stakeholders to address the pressing environmental challenges stemming from the widespread use of land vehicles in the region, ultimately contributing to a more sustainable and environmentally responsible future for ASEAN nations.

Conclusion

This study investigates the impact of the automobile industry on CO_2 emissions across major ASEAN vehicle-producing countries, namely Vietnam, the Philippines, Indonesia, Malaysia, and Thailand, over the period 1999–2022. The study uses FMOLS and DOLS estimating methods to show that total vehicle production, foreign direct investment (FDI), and economic growth all have a big role in rising CO_2 emissions. The robustness check using the Panel ARDL model, on the other hand, shows a somewhat different pattern: FDI and vehicle production are still important, but economic growth is no longer important, and population growth becomes a major cause of emissions. These differences show that models are sensitive to different things and suggest that the effects of population growth and economic growth on the environment vary on the situation and the approach used. These differences between models may be due to different ideas about lag structure, dynamic relationships, or country-level differences that ARDL captures but FMOLS/DOLS does not. It is important to know these differences in order to make policies that take into account both short- and long-term changes in the environment. The findings highlight the substantial environmental cost associated with the growth of the automobile industry. Vehicle production is a critical factor in CO_2 emissions because it not only increases the number of vehicles on the road, leading to greater fuel consumption and emissions, but also involves energy-intensive manufacturing processes that contribute directly to industrial emissions. Increased vehicle production directly raises emissions, while rapid economic expansion and industrial activities further exacerbate the problem. However, the study also recognizes that economic growth, if coupled with investment in cleaner technologies and a transition to greener industries, holds potential for mitigating CO_2 emissions over time. These findings are consistent with existing literature that links industrial expansion, particularly in the automobile sector, with environmental degradation. However, this study expands on prior work by providing new evidence from major ASEAN economies, a region that has been less explored in this context. It emphasizes that without strict environmental regulations and incentives for cleaner production, industrial growth will continue to drive up emissions.

Overall, the results answer the research hypotheses by showing that the automobile industry and foreign direct investment (FDI) always add to CO_2 emissions in ASEAN nations. But the effects of population increase and economic growth are different depending on the method used to get the estimates, which shows that their effects rely on the model. These differences show how important it is to have policy options that take into consideration the sectoral and demographic contexts when dealing with environmental problems. These results have important policy implications. Encouraging the production and adoption of electric vehicles (EVs), such as through targeted tax breaks like reduced import duties, corporate tax exemptions for EV manufacturers, and consumer subsidies for EV purchases, providing fiscal incentives for green manufacturing practices, and expanding public transportation infrastructure are critical steps toward reducing the environmental footprint of land transportation. Specifically, investments should prioritize the development of mass rapid transit (MRT) systems, bus rapid transit (BRT) corridors, and the electrification of public bus fleets in rapidly urbanizing ASEAN cities such as Jakarta, Kuala Lumpur, and Manila. Governments should implement robust regulatory frameworks, promote research and development in sustainable automotive technologies, and strengthen environmental standards across the transportation sector. Given the finding that foreign direct investment (FDI) can increase emissions, policymakers should introduce specific environmental regulations that require foreign investors to adopt cleaner production technologies and sustainable operational practices. Incentives, such as tax benefits or streamlined permit processes, could be offered to foreign firms that meet green certification standards within ASEAN countries. Moreover, addressing population growth's impact on emissions will require integrated uban planning and greater investments in sustainable public services. Initiatives such as promoting transit-oriented development (TOD) and enhancing non-motorized transport infrastructure (e.g., cycling lanes and pedestrian pathways) should be incorporated into urban planning strategies. Cross-sector collaboration, involving policymakers, industry leaders, and civil society, will be vital for achieving a low-carbon transition.

Limitations and future research directions

Though this research met its main goal, it is important to mention a number of limitations. First, the field of variables is limited and this could lead to omitted variable bias. The policy interventions, renewable energy, financial development and green finance were not considered but might have a significant impact on the CO_2 emission. Second, the applied econometric methods (FMOLS, DOLS, and ARDL) are very useful to give strong long-run and short-run explanations but lack the ability to identify complex nonlinear or threshold effects. Future studies may utilize some sophisticated methods like panel threshold models or machine learning methods to deal with these dynamics. Third, despite the location of the study in the framework of the ASEAN-5, one should be careful when extending the results to other regions since the differences in socioeconomic framework, technological achievements, and environmental policies can influence the results. Lastly, the research is concentrated on the automobile industry, considering that the reader could have gained more insights on the research field, transportation-related emissions, by considering a wider industry, such as aviation and shipping.

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Declarations

Ethics approval and consent to participate NA.

Consent for publication NA.

Conflict of interest The authors declare no competing interests.

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