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Environmental Pressures and Sustainable Consumption and Production in ASEAN Countries: The Role of Ecological Footprint and CO_2

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ABSTRACT

Sustainable consumption and production (SCP), aligned with the UN Sustainable Development Goal 12 (SDG 12), has become a central pillar of the global sustainability agenda, particularly in developing regions under increasing environmental pressure. This study examines the effects of Ecological Footprint (EFC) and CO_2 on SCP across nine ASEAN countries from 2000 to 2023. To account for heterogeneous associations across different levels of sustainability performance, this study applies pooled quantile regression (PQR) to the panel dataset, estimating conditional relationships across the 10th to 90th quantiles. The findings reveal significant heterogeneity in the relationship between environmental pressures and SDG 12 performance across the conditional distribution. At the median quantile, EFC exhibits a positive and statistically significant coefficient of 1.948484, indicating that a one-unit increase in logged EFC is associated with a 1.948484-point increase in the SDG 12 index, ceteris paribus. In contrast, CO_2 shows a negative and statistically significant coefficient of −1.541278 at the median quantile, indicating that a one-unit increase in logged CO_2 is associated with a 1.541278-point decrease in the SDG 12 index, ceteris paribus. These effects also vary across the quantile distribution, confirming substantial heterogeneity in the relationship between environmental pressures and SCP. The regional heterogeneity analysis further demonstrates that the effects of environmental pressures differ between leading and non-leading ASEAN economies, reflecting disparities in economic development, institutional capacity, and sustainability readiness. These findings support the ecological modernization perspective, emphasizing that environmental conditions are not merely outcomes of economic activities but also important determinants of sustainability performance. The study contributes to the literature by positioning environmental pressures as drivers of SDG 12 achievement and provides policy insights for advancing SCP in ASEAN countries.

1. INTRODUCTION

The adoption of the 2030 Agenda for Sustainable Development has intensified global efforts to balance economic prosperity, social well-being, and environmental sustainability. Among the seventeen Sustainable Development Goals (SDGs), SDG 12, which promotes sustainable consumption and production (SCP) [1], occupies a central position because it directly addresses the efficiency of resource utilization, waste generation, environmental degradation, and the sustainability of production systems [2, 3]. Achieving SDG 12 is increasingly recognized as a prerequisite for attaining several other goals, including climate action, responsible resource management, biodiversity conservation, and sustainable economic development [4, 5]. Despite growing international commitments, many countries continue to face substantial challenges in transitioning from conventional growth models toward more sustainable production and consumption patterns.

The urgency of SDG 12 has become more pronounced in recent decades due to the unprecedented increase in resource extraction and environmental pressures associated with economic expansion [6, 7]. Global material consumption has more than tripled since the 1970s [8], while resource use continues to grow at a pace that exceeds the regenerative capacity of ecosystems [9]. Such trends have raised concerns regarding the long-term sustainability of economic activities, particularly in developing and emerging economies where industrialization, urbanization, and population (POP) growth continue to accelerate [10, 11]. Understanding the determinants that either facilitate or hinder SCP has become an important area of inquiry within sustainability and development research.

Environmental pressures are frequently identified as one of the most significant barriers to sustainable development [12-14]. Among various indicators, Ecological Footprint (EFC) has emerged as a comprehensive measure of environmental demand, reflecting the amount of biologically productive land

and water required to sustain human activities and absorb generated waste [15, 16]. A growing EFC indicates increasing pressure on natural ecosystems and signals unsustainable patterns of resource consumption [17, 18]. As production systems expand and consumer demand rises, excessive EFCs may undermine the achievement of SDG 12 by intensifying resource depletion and reducing environmental carrying capacity.

CO_2 represents another critical dimension of environmental pressure. CO_2 emissions are widely regarded as the primary contributor to global climate change and are closely associated with fossil fuel consumption, industrial production, transportation activities, and energy-intensive economic growth [19-21]. High levels of CO_2 often reflect inefficient production structures and unsustainable consumption behaviors [22-24]. Countries characterized by increasing CO_2 may encounter greater difficulties in promoting responsible production processes and resource-efficient consumption patterns, thereby slowing progress toward SDG 12 targets.

The relationship between environmental pressures and sustainable development is particularly relevant in the ASEAN region. Over the past two decades, ASEAN countries have experienced remarkable economic growth, rapid urbanization, expanding industrial sectors, and increasing integration into global value chains [25, 26]. These developments have contributed significantly to improvements in income levels and living standards. Nevertheless, they have also generated substantial environmental challenges, including rising EFCs, increasing greenhouse gas emissions, accelerated resource extraction, and mounting waste generation [27-29]. As a result, ASEAN represents an important empirical setting for examining how environmental pressures influence the pursuit of SCP.

Despite increasing scholarly attention to sustainability issues, the existing literature has predominantly focused on environmental outcomes such as CO_2, ecological degradation, EFC, and climate change. Numerous studies have investigated the determinants of environmental degradation, including economic growth, Foreign Direct Investment (FDI), energy consumption, trade openness, and technological development. Comparatively limited attention has been devoted to understanding the factors influencing SDG 12 performance itself. In particular, studies that explicitly examine SCP as an outcome variable remain relatively scarce, especially within the developing and emerging economies.

Furthermore, previous empirical evidence concerning EFC and CO_2 has primarily treated these indicators as dependent variables rather than explanatory factors. This conventional approach provides important insights into environmental degradation but offers limited understanding of how environmental pressures may affect broader sustainability objectives. Rather than representing SDG 12 itself, EFC and CO_2 capture environmental pressures generated by prevailing consumption, production, and energy-use patterns. These pressures may subsequently constrain the ability of countries to maintain resource-efficient production systems, adopt cleaner technologies, and implement environmentally responsible consumption practices. Therefore, this study reverses the conventional analytical perspective by examining whether the existing level of environmental pressure is systematically associated with differences in SDG 12 performance, while acknowledging that the relationship may also involve feedback mechanisms.

Another limitation of existing studies concerns the heterogeneity of sustainability outcomes across countries. ASEAN economies differ substantially in terms of income levels, industrial structures, resource dependence, environmental governance, and sustainability capacities. The effects of EFC and CO_2 on SCP may not be uniform across different levels of SDG 12 performance. Conventional mean-based estimation techniques may fail to capture these heterogeneous effects, potentially obscuring important policy-relevant relationships among countries with varying sustainability achievements.

Importantly, this study does not conceptualize EFC and CO_2 as components or direct measures of SDG 12. Rather, they are treated as broader environmental pressure variables that can constrain or facilitate the implementation of SCP practices. EFC captures the aggregate demand that human activities place on biologically productive ecosystems, while CO_2 captures the carbon-intensive dimension of production and energy use. These pressures can affect SDG 12 performance through resource availability, production efficiency, environmental costs, and the capacity of economies to shift toward cleaner technologies and more resource-efficient production systems. Thus, the analytical direction adopted in this study is that prevailing environmental pressures constitute contextual conditions that may influence a country's ability to achieve SCP outcomes. This conceptualization does not imply that EFC or CO_2 are exclusively causal determinants; rather, the empirical analysis evaluates their conditional association with SDG 12 performance while recognizing the possibility of feedback relationships between environmental pressures and sustainability outcomes.

Beyond examining the direct associations between environmental pressures and SDG 12 performance, this study considers the possibility that these relationships vary with countries' levels of economic development. The conceptual premise is that environmental pressures do not operate independently of the broader economic system. In particular, economic development may shape the relationship between CO_2 and SCP by reflecting differences in production structures, technological capabilities, and resource-use patterns. Accordingly, the relationship between CO_2 and SDG 12 performance may differ across levels of economic development rather than follow a uniform pattern across ASEAN countries. To examine this possibility, the study introduces an interaction between CO_2 and Gross Domestic Product (GDP) to test whether economic development moderates the relationship. This approach provides a testable extension of the baseline model by assessing whether the association between CO_2 and SDG 12 performance varies with economic development. The analysis is intended to identify conditional associations rather than establish causal mechanisms.

This study contributes to the sustainability literature in several important ways. Unlike most previous studies that model EFC and CO_2 as environmental outcomes, this research conceptualizes them as environmental pressures that influence SCP performance. The study places SDG 12 at the center of the analysis, addressing a relatively underexplored area within empirical sustainability research. By focusing on nine ASEAN countries during the period 2000–2023, the study provides long-term regional evidence from one of the world's most dynamic economic regions, where sustainability challenges continue to intensify alongside economic transformation. These contributions offer a new perspective on the interaction between environmental pressures and sustainable

development objectives.

This study aims to investigate the effects of EFC and CO_2 on SCP in ASEAN countries over the period 2000–2023. By examining how environmental pressures shape SDG 12 performance, the study seeks to enrich the growing literature on sustainability transitions and environmental governance. The findings are expected to contribute to both academic and policy discussions by providing evidence on the environmental factors that influence SCP, thereby supporting the formulation of more effective strategies for achieving SDG 12 and advancing sustainable development across the ASEAN region.

2. LITERATURE REVIEW

The growing discourse on sustainable development has shifted scholarly attention from economic growth-centered paradigms toward multidimensional frameworks that incorporate environmental sustainability and resource efficiency. SCP has emerged as a critical mechanism for achieving long-term sustainability objectives [30, 31]. SCP emphasizes the efficient use of natural resources, the minimization of environmental externalities, and the promotion of production systems that balance economic prosperity with ecological preservation [32, 33]. The determinants of SCP have become an important area of investigation within environmental economics and sustainability studies.

A substantial body of literature suggests that environmental conditions play a decisive role in shaping sustainability outcomes. According to ecological modernization theory, environmental sustainability can be achieved when economic systems successfully integrate ecological considerations into production and consumption processes [34, 35]. When environmental pressures exceed ecological thresholds, the capacity of economies to maintain sustainable development trajectories becomes increasingly constrained [36-38]. This perspective implies that environmental degradation is not merely an outcome of economic activities but may also influence the effectiveness of sustainability-oriented policies and development initiatives.

The analytical rationale for treating EFC as an explanatory variable rests on its role as a measure of environmental pressure rather than as a direct measure of SCP performance. A higher EFC indicates greater demand for biological resources and ecological capacity. Such pressure can influence SDG 12 performance through several channels. First, increasing pressure on natural resources can raise the scarcity and economic costs of resource inputs, thereby reducing incentives or capacity to maintain resource-efficient production. Second, ecological stress can increase the costs associated with waste management, ecosystem degradation, and environmental remediation. Third, persistent pressure on ecological systems may encourage governments and firms to strengthen resource-efficiency measures, cleaner production practices, and environmental regulations. Consequently, EFC may be associated with SDG 12 performance through both constraining and adjustment mechanisms, making its empirical effect theoretically ambiguous and suitable for distributional investigation.

Among the indicators commonly used to assess environmental pressure, EFC has received considerable attention due to its comprehensive measurement of human demand on natural ecosystems. Several studies have demonstrated that rising EFCs are associated with excessive resource extraction, ecosystem degradation, and declining environmental quality. Increasing EFCs have been associated with unsustainable resource utilization patterns that threaten long-term environmental sustainability [39-41]. These findings suggest that countries experiencing higher ecological pressure may encounter greater challenges in maintaining sustainable production systems and responsible consumption behavior.

The relationship between EFC and sustainability performance can also be explained through resource efficiency mechanisms. SCP requires production systems capable of generating economic value while minimizing environmental costs [42]. Elevated EFCs often indicate inefficiencies in resource use, overconsumption of natural capital, and excessive waste generation [43, 44]. Unsustainable resource utilization has been found to constrain economies' ability to transition towards environmentally responsible production structures, thereby hindering broader sustainability objectives [45, 46].

Another strand of literature highlights the role of CO_2 as a key indicator of environmental stress. CO_2 is frequently associated with fossil fuel dependence, industrial expansion, and carbon-intensive production activities [23, 47]. Existing empirical studies generally report a close relationship between increasing CO_2 and environmental degradation. High emission levels have been associated with structural inefficiencies in energy systems and production processes [48-50]. These conditions may reduce environmental resilience and complicate efforts to achieve SDGs.

From a sustainability perspective, CO_2 may influence consumption and production patterns through multiple channels. First, carbon-intensive production systems often rely heavily on non-renewable resources and inefficient technologies [51, 52]. Second, rising emissions contribute to environmental degradation that may increase the social and economic costs of production activities [48, 53]. Third, emission-intensive growth models may encourage consumption patterns that prioritize short-term economic gains over long-term environmental sustainability [54, 55]. Lower-carbon development pathways are increasingly viewed as essential for promoting SCP outcomes.

CO_2 can therefore be interpreted as an environmental pressure that reflects the carbon intensity of prevailing production and consumption systems. Higher emissions may indicate greater dependence on fossil-fuel-based technologies, inefficient energy use, and production structures that generate larger environmental externalities. These conditions can make the transition toward sustainable production more difficult by increasing adjustment costs and technological requirements. At the same time, persistent carbon pressure may stimulate environmental regulation, technological upgrading, energy efficiency, and the adoption of cleaner production systems. Accordingly, the expected relationship between CO_2 and SDG 12 performance is not necessarily mechanical or unidirectional. Instead, CO_2 represents a measurable environmental condition through which the interaction between existing production structures and sustainability transitions can be empirically assessed.

Recent studies have also emphasized the importance of integrating environmental indicators into broader sustainability assessments. Rather than treating environmental degradation solely as an outcome variable, emerging research

increasingly recognizes environmental conditions as fundamental determinants of sustainable development performance. Environmental sustainability indicators have been found to significantly influence the achievement of multiple SDGs by shaping resource availability, ecosystem services, and long-term economic resilience [56-58]. This perspective supports the argument that environmental pressures should be incorporated into analyses of SCP performance.

Theoretical and empirical evidence further indicates that the relationship between environmental pressures and sustainability outcomes may differ across countries. Environmental Kuznets Curve arguments suggest that sustainability transitions are influenced by differences in economic structures, technological capacities, institutional quality, and environmental governance [59, 60]. Countries with similar levels of environmental pressure may exhibit different sustainability outcomes depending on their ability to adopt cleaner technologies, improve resource efficiency, and implement effective environmental policies [61, 62]. Such heterogeneity is particularly relevant in a region characterized by diverse development trajectories.

Within ASEAN, these dynamics are especially important due to substantial disparities in economic development, industrialization patterns, and environmental management capacities. While some ASEAN countries have made significant progress in implementing sustainable production initiatives and environmental regulations, others continue to face challenges related to resource dependence, carbon-intensive growth, and ecological degradation [63, 64]. Consequently, understanding how EFC and CO_2 influence SCP across ASEAN countries is essential for designing effective sustainability policies and identifying pathways toward more balanced and resilient development.

Although the literature has extensively examined the determinants of EFC, CO_2, and environmental degradation, several important gaps remain. First, most existing studies treat EFC and CO_2 as dependent variables, focusing on identifying their economic and institutional determinants rather than evaluating their impacts on sustainability outcomes. Second, empirical investigations that explicitly employ SCP (SDG 12) as the primary outcome variable remain relatively limited, particularly within developing and emerging economies. Third, previous studies often analyze environmental indicators independently without simultaneously assessing the combined influence of EFC and CO_2 on sustainability performance. Finally, evidence from ASEAN remains scarce despite the region's growing environmental challenges and increasing commitment to the SDGs. Therefore, this study addresses these gaps by examining how EFC and CO_2 influence SCP across nine ASEAN countries during the period 2000–2023, providing new empirical insights into the environmental determinants of SDG 12 achievement.

3. DATA AND METHODOLOGY

This study employs balanced panel data covering nine ASEAN countries, namely Indonesia, Malaysia, Singapore, Thailand, the Philippines, Vietnam, Brunei Darussalam, Cambodia, and Laos, over the period 2000–2023. The selected period captures important economic, environmental, and sustainability transitions within the ASEAN region, including rapid industrialization, increased regional economic integration, growing environmental pressures, and the implementation of the SDGs. The use of panel data enables the analysis to account for both cross-country heterogeneity and temporal dynamics, providing a comprehensive understanding of the relationship between environmental pressures and SCP [65].

The study covers the period 2000–2023, which includes both the pre-SDG period (2000–2014) and the period following the adoption of the SDGs in 2015 (2015–2023). Although the historical SDG 12 scores are available for the entire study period, the interpretation of these scores requires caution because observations before 2015 are retrospectively constructed rather than contemporaneous assessments under the formally adopted SDG framework. Consequently, the baseline estimates capture associations over the full observation period and do not, by themselves, establish whether these relationships changed following the adoption of the SDGs. This temporal distinction should be considered when interpreting the estimated relationships between environmental pressures and SDG 12 performance.

The selection of ASEAN as the study area is motivated by its strategic role as one of the world's fastest-growing economic regions. ASEAN countries have experienced significant structural transformation during the last two decades, characterized by increasing urbanization, industrial expansion, and integration into global production networks [66]. At the same time, the region faces mounting environmental challenges, including rising CO_2, resource depletion, biodiversity loss, and ecological degradation [67]. The nine countries included in this study collectively represent diverse economic development stages, institutional capacities, and environmental management systems, thereby providing an appropriate setting for investigating sustainability-related issues from a comparative perspective.

The dependent variable is the SDG 12 score, representing country-level performance in achieving SCP. The data were obtained from the Sustainable Development Report 2024 (SDR 2024) database. Specifically, the historical observations were taken from the database's "Backdated SDG Index" worksheet, which provides retrospectively calculated SDG Index and goal scores for 2000–2023. According to the database documentation, these historical scores are calculated using time-series data, with values carried forward in years for which data are missing. Therefore, observations before the adoption of the SDGs in 2015 represent retrospectively constructed scores rather than contemporaneous assessments under the formally adopted SDG framework. The SDG 12 variable used in this study corresponds to the goal-level score reported in the SDR 2024 database. The original database covers 182 countries over 2000–2023; the present study extracts observations for the nine ASEAN countries included in the analytical sample. The historical values are taken from the published database rather than independently backcast by the authors. The use of this retrospective series should be considered when interpreting changes in SDG 12 performance over time, particularly across the pre-2015 and post-2015 periods.

This study focuses on SDG 12 (SCP) as the dependent variable because it occupies a central position within the sustainable development framework. Unlike environmental indicators that primarily measure ecological outcomes, SDG 12 reflects the extent to which countries successfully promote resource efficiency, responsible consumption patterns,

sustainable industrial processes, and environmentally sound production systems. Furthermore, SDG 12 serves as a connecting goal that influences the achievement of multiple sustainability objectives, including climate action, ecosystem conservation, and sustainable economic growth. Therefore, understanding the determinants of SDG 12 performance is essential for formulating effective sustainability policies in developing and emerging economies.

This study uses the composite SDG 12 score from the Sustainable Development Report 2024 as the dependent variable to capture country-level performance in SCP. Although this composite measure provides a consistent summary indicator for the empirical analysis, it does not separately identify the individual dimensions underlying SDG 12 performance. Consequently, the estimated relationships should be interpreted as associations with the overall SDG 12 score rather than with specific outcomes such as material consumption, waste generation, resource productivity, or energy efficiency. The analysis is also constrained by the availability of comparable country-level data over the full study period, which limits the use of alternative indicators and disaggregated SDG 12 measures for robustness testing.

EFC and CO_2 are employed as the primary explanatory variables because they represent two complementary dimensions of environmental pressure that are conceptually distinct from the SDG 12 performance index. EFC captures the aggregate demand placed on biologically productive ecosystems, whereas CO_2 reflects the carbon intensity associated with energy use, production, and economic activity. In this study, these variables are positioned as environmental conditions that may influence the capacity of countries to achieve SCP outcomes through resource availability, production efficiency, environmental costs, technological adjustment, and environmental policy responses. This specification should not be interpreted as establishing a strictly unidirectional causal relationship. Rather, the empirical model examines the conditional association between prevailing environmental pressures and SDG 12 performance while controlling for economic, investment, fiscal, and demographic characteristics. The distinction is important because EFC and CO_2 are treated as explanatory environmental-pressure indicators, whereas SDG 12 represents the broader sustainability performance outcome captured by the SDG 12 index.

The interpretation of the relationship between EFC and SDG 12 requires consideration of the conceptual and measurement differences between the two indicators. EFC represents the demand placed on ecological resources, whereas SDG 12 measures progress towards responsible consumption and production. These concepts are related but are not equivalent: a higher EFC does not necessarily indicate better SCP performance. The estimated positive association may instead reflect differences in economic development, production capacity, consumption patterns, or the availability of underlying data. In addition, the possibility of overlap between the underlying data or measurement components of the two indicators needs to be considered when interpreting the estimates. Therefore, the positive coefficient on EFC should be understood as an empirical association within the study's measurement framework, rather than evidence that greater ecological pressure improves sustainability.

EFC is obtained from the Global Footprint Network's National Footprint and Biocapacity Accounts, 2026 Edition (data and metadata version 1.0). Specifically, this study uses the "EFC of Consumption – Total" series, identified by the record code "EFConsTotGHA" on the EFC Explorer open data platform. The variable represents the national total EFC rather than the per-capita measure and is expressed in global hectares (gha). As a consumption-based indicator, it captures the ecological demand associated with a country's consumption, calculated by accounting for domestic production, imports, and exports. Accordingly, the measure reflects the aggregate EFC attributable to national consumption rather than the average footprint per individual or the EFC of domestic production alone. The original national total values are retained in the analytical dataset and subsequently transformed into their natural logarithms for econometric estimation. The list of variables can be seen in Table 1.

Table 1. Variables description and data sources

Variable	Description	Source
Sustainable consumption and production (SCP)—SDG 12	SDG 12 goal-level score measuring country performance in SCP, obtained from the retrospectively calculated historical series (Index Score)	Sustainable Development Report 2024 (SDR 2024), "Backdated SDG Index" worksheet
Ecological Footprint (EFC)	National total EFC of Consumption for each country-year observation (not expressed on a per-capita basis), measured in global hectares (gha)	Global Footprint Network, National Footprint and Biocapacity Accounts, 2026 Edition, Data and Metadata Version 1.0; series code: EFConsTotGHA
CO_2	National territorial fossil CO_2 from fossil fuel combustion and oxidation, including cement production and excluding international aviation and maritime bunker fuels. Measured in million tonnes of carbon per year (MtC/year), without additional unit conversion	Global Carbon Budget 2025, National Fossil CO_2 dataset, Version 0.3, "Territorial Emissions" worksheet
Foreign Direct Investment (FDI)	Net inflows of FDI as a percentage of economic activity (% of GDP)	World Development Indicators (World Bank)
Gross Domestic Product (GDP)	Economic output representing the level of economic development (Current US$)	World Development Indicators (World Bank)
Government Expenditure (GOEX)	Government final consumption expenditure representing public sector involvement in economic activities (Current US$)	World Development Indicators (World Bank)
Population (POP)	Total POP representing demographic pressure on resources and production systems (Persons)	World Development Indicators (World Bank)

CO_2 data are obtained from the Global Carbon Budget 2025, specifically the National Fossil CO_2 dataset (Version 0.3), using the "Territorial Emissions" worksheet. The selected series is entitled "Fossil CO_2 emissions by country

(territorial)" and represents national territorial emissions from fossil fuel combustion and oxidation, including cement production, while excluding emissions from international aviation and maritime bunker fuels. The original observations are expressed in million tonnes of carbon per year (MtC/year), as explicitly indicated in the dataset documentation. In this study, the original measurement unit is retained without applying the conversion factor of 3.664 to obtain million tonnes of carbon dioxide per year ($MtCO_2$/year). Accordingly, the variable used in the regression models represents the natural logarithm of national territorial fossil CO_2 measured in MtC/year. This specification ensures consistency between the original data source, the analytical dataset, and the variable definition employed in the econometric estimations.

To improve the robustness of the empirical analysis, several control variables are incorporated into the model. FDI is included because international investment can facilitate technology transfer and enhance production efficiency, although it may also increase environmental pressure depending on the nature of investment activities. GDP is used to capture the level of economic development, which may influence sustainability performance through income effects and technological progress. Government Expenditure (GOEX) is incorporated to represent the role of public intervention and policy support in promoting sustainability initiatives. Finally, POP is included to account for demographic pressures that affect resource consumption, production demand, and environmental sustainability. The combination of these variables allows for a more comprehensive assessment of the determinants of SCP within ASEAN countries.

A key issue in specifying the empirical model concerns the extent to which aggregate environmental measures capture environmental pressure or simply reflect differences in national scale. Because total EFC and CO_2 tend to vary with POP and economic activity, their estimated effects may be influenced by cross-country differences in demographic and economic size. The inclusion of POP as an independent control may not fully address this issue, especially when environmental aggregates are closely associated with broader scale-related factors. Therefore, the estimated relationships should be interpreted in light of the units in which environmental variables are measured and the potential influence of POP size. Further robustness checks based on per-capita environmental measures, together with an interaction term between economic development and CO_2, could provide additional evidence on whether the main results persist after accounting for these scale-related concerns.

Several pre-estimation procedures are conducted to ensure the robustness and validity of the empirical results. First, cross-sectional dependence (CSD) tests are employed to examine whether shocks or disturbances occurring in one ASEAN country may affect other countries within the region. This issue is particularly relevant given the increasing economic integration, trade interdependence, environmental spillovers, and regional cooperation frameworks among ASEAN member states. Based on Polcyn et al. [68], to detect the presence of CSD, this study applies three complementary approaches, namely the Pesaran CD test, the scaled Lagrange Multiplier (LM) test, and the Breusch–Pagan LM test, as specified in Eqs. (1) and (2):

$$CSD = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N.3}\rho_{ij} \quad (1)$$

$$CSD = \sqrt{\frac{3T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij} \quad (2)$$

The application of multiple CSD tests enhances the reliability of the diagnostic procedure and minimizes the risk of biased estimations arising from cross-country dependence. Following the CSD analysis, panel unit root testing is performed using the Cross-sectionally Augmented IPS (CIPS) test based on the Cross-sectional Augmented Dickey–Fuller (CADF) framework [69]. Based on a previous study [70], the CIPS test is particularly suitable because it accommodates CSD that commonly characterizes macro-panel datasets involving interconnected economies. The CIPS statistic is expressed in Eq. (3):

$$CIPS = N^{-1}\sum_{i=1}^{n} CADF \quad (3)$$

Subsequently, model specification testing is conducted to determine the most appropriate panel structure between the fixed effect model (FEM) and the random effect model (REM). Given the substantial heterogeneity among ASEAN countries in terms of economic development, environmental governance, industrial structures, and sustainability performance, the FEM is expected to provide a more appropriate baseline specification. The selection is formally verified through standard panel specification procedures before proceeding to the pooled quantile regression (PQR) estimation.

In this study, PQR is applied to the panel dataset to investigate whether the associations between environmental pressures and SCP (SDG 12) differ across the conditional distribution of sustainability performance. The estimation uses the standard quantile regression (QREG) procedure in EViews, based on the least absolute deviations (LAD) criterion. The country-year observations are pooled for the quantile estimation, and the specification does not include country-specific or year-specific fixed effects. Therefore, the estimated coefficients describe conditional associations across the pooled distribution of SDG 12, rather than within-country effects after controlling for unobserved country heterogeneity or common year-specific effects. This distinction is important because the quantile estimates should not be interpreted as fixed-effects PQR estimates. The separate fixed-effects model reported in this study is presented independently as the baseline mean-based panel specification.

The baseline panel regression model is specified as follows:

$$y_{it} = x_{it}\beta + \alpha_i + u_{it}, i = 1,2,\dots,N; t = 1,2,\dots,T \quad (4)$$

where, *i* denotes the cross-sectional units (countries), *t* denotes the time dimension, X_{it} represents the vector of explanatory variables, β is the vector of slope coefficients, α_i captures the unobserved country-specific fixed effects, and ε_{it} denotes the error term. The conditional quantile specification of the panel model is formulated as [71]:

$$Q_{yit}(\tau_j|x_{it},\alpha_i) = x'_{it}\beta(\tau_j) + \alpha_i, i = 1,2,\dots,N; t = 1,2,\dots,T \quad (5)$$

This study employs the QREG estimator implemented in EViews to examine the heterogeneous relationships between environmental pressures and SCP across the conditional

distribution of SDG 12 performance. The estimation follows the LAD approach, with separate coefficient estimates obtained across nine quantiles, ranging from the 10th to the 90th percentiles. Unlike conventional mean-based regression, QREG allows the estimated relationships between the explanatory variables and SDG 12 performance to vary across different points of the conditional distribution. The estimation is conducted using the standard QREG procedure in EViews and does not employ a Koenker-type penalized fixed-effects quantile estimator or an explicit penalty-selection procedure.

Regarding statistical inference, the coefficient covariance matrix is estimated using the Huber Sandwich covariance estimator. The sparsity parameter is estimated using the kernel method based on residuals, with the Hall–Sheather bandwidth selection procedure and a size parameter of 0.05. The Rankit (Cleveland) method is used for quantile calculation, while the Epanechnikov kernel is employed for kernel-based sparsity estimation. No observation weighting is applied. The estimation procedure uses a maximum of 500 iterations and zero starting values. These settings are consistently applied across the estimated quantile specifications. No bootstrap procedure is employed in the reported QREG analysis.

Based on the variables employed in this study, the empirical PQR model is specified as:

$$\begin{gathered} Q_\tau(SDG\ 12)_{it}|X_{it}) = \beta_0(\tau) \\ +\beta_1(\tau)LnECF_{it} + \beta_2(\tau)LnCO_{2_{it}} + \beta_3(\tau)LnFDI_{it} \\ +\beta_4(\tau)LnGDP_{it} + \beta_5(\tau)LnGOEX_{it} \\ +\beta_6(\tau)LnPOP_{it} + \varepsilon_{it}(\tau) \end{gathered} \quad (6)$$

where, SDG 12 represents the SCP Index, LnEFC denotes Logarithm of EFC, $LnCO_2$ represents Logarithm of CO_2, LnFDI refers to Logarithm of Foreign Direct Investment, LnGDP represents Logarithm of Gross Domestic Product, LnGOEX denotes Logarithm of Government Expenditure and LnPOP refers to Logarithm of Population. The coefficient estimates obtained at different quantiles allow the assessment of whether environmental pressures exert heterogeneous effects across countries with varying levels of SCP performance.

Regarding the fixed-effects estimation, the model is estimated using EViews with both cross-section and period fixed effects. The coefficient covariance method is specified as Ordinary, with no GLS weighting applied. Consequently, the standard errors reported for the fixed-effects estimates are conventional ordinary standard errors generated by the EViews estimation procedure. The estimation is conducted using the Equation Estimation interface, with the cross-section and period effects specified as fixed. It is important to distinguish the inclusion of cross-section and period fixed effects from the covariance estimation procedure: the inclusion of these fixed effects does not, by itself, ensure that the standard errors are robust to CSD. Accordingly, the inference from the fixed-effects estimates is interpreted with caution in view of the CSD identified in the diagnostic tests.

Eq. (6) serves as the primary analytical framework of this study, enabling the investigation of how EFC and CO_2 influence SDG 12 achievement across different points of the sustainability distribution. By examining lower, middle, and upper quantiles, the analysis provides deeper insights into whether environmental pressures affect countries with weak sustainability performance differently from those that have already achieved relatively high levels of SCP.

The empirical strategy is designed to examine the associations between environmental pressures and SDG 12 performance across ASEAN countries and across different conditional quantiles. The fixed-effects and PQR estimates account for specified model characteristics and observed heterogeneity, but they do not, by themselves, establish causal relationships. In the absence of an explicit identification strategy addressing potential endogeneity and reverse causality, the estimated coefficients are interpreted as conditional associations rather than causal effects. Accordingly, the empirical findings provide evidence on the direction and distribution of statistical relationships within the specified models, while causal interpretations remain beyond the scope of the present analysis.

4. RESULTS AND DISCUSSION

4.1 Descriptive statistics

Before conducting the econometric estimations, it is important to examine the descriptive characteristics of the variables included in the study. Descriptive statistics provide an initial overview of the distributional properties of the dataset and help identify the extent of variation across countries and over time. Furthermore, this preliminary analysis offers useful insights into the overall behavior of the variables prior to the implementation of the PQR framework.

Table 2 presents the summary statistics of SCP (SDG 12), EFC, CO_2, FDI, GDP, GOEX and POP for the nine ASEAN countries during the period 2000–2023. Overall, the results indicate substantial heterogeneity across the sample countries, reflecting differences in economic size, demographic characteristics, environmental conditions, and sustainability performance. Such variation is expected given the diverse development trajectories and structural characteristics of ASEAN economies.

The dispersion measures reveal that economic and environmental indicators exhibit considerable variability throughout the observation period. Variables associated with economic activity, environmental pressure, and demographic conditions display relatively wide distributions, suggesting the existence of significant cross-country differences and temporal fluctuations. These patterns are consistent with the contrasting levels of industrialization, resource utilization, and POP dynamics observed across ASEAN member states. The presence of substantial variability in the dataset further supports the suitability of employing panel data techniques capable of capturing heterogeneous effects across countries.

Regarding the distributional characteristics, most variables exhibit positive skewness, indicating that observations tend to be concentrated at lower values with a smaller number of relatively large observations. This pattern reflects the presence of several countries that possess considerably larger economic, demographic, or environmental profiles compared to the regional average. In addition, the kurtosis values suggest that the distributions vary across variables, with some indicators displaying more concentrated observations around the mean while others exhibit heavier tails. These findings imply that the dataset may contain heterogeneous distributional patterns, thereby reinforcing the relevance of PQR as an appropriate analytical approach for examining differential effects across various levels of SCP performance.

The descriptive statistics were cross-checked against the final analytical dataset, and the reported values are retained.

The variables are presented using the measurement scales indicated in the table, which should be distinguished from their logarithmic transformations where applicable in the subsequent empirical analysis.

Following the descriptive statistics analysis, the correlation matrix is examined to provide an initial overview of the relationships among the variables included in the model. Correlation analysis serves as a preliminary diagnostic tool to identify the direction and strength of linear associations between variables before conducting further econometric estimations. In addition, this analysis helps assess the potential presence of multicollinearity among the explanatory variables.

Table 3 presents the pairwise correlation coefficients among SDG 12, EFC, CO_2, FDI, GDP, GOEX, and POP. The results indicate that the explanatory variables exhibit varying degrees of association with SCP performance. While some variables display positive relationships, others show negative associations, suggesting that the determinants of SDG 12 achievement may operate through different economic, demographic, and environmental channels. These findings provide an initial indication that the selected variables capture distinct dimensions of sustainability-related dynamics across ASEAN countries.

Furthermore, the pairwise correlations among the explanatory variables do not indicate severe linear dependence. The highest correlation is observed between LnFDI and LnGDP (0.697723), followed by LnGOEX and LnFDI (0.680653) and LnGDP and $LnCO_2$ (0.647355). Although these values indicate moderate associations among several economic and environmental variables, none suggests an excessively strong pairwise relationship. Therefore, the correlation matrix provides preliminary evidence that severe multicollinearity is unlikely to explain the magnitude of the estimated LnGDP coefficient. Nevertheless, correlation analysis is regarded as a preliminary diagnostic, and the results are interpreted accordingly.

Table 2. Summary statistics for each variable

Variables	Obs	Mean	Variance	Std. Dev	Skewness	Kurtosis	Minimum	Maximum
SDG 12	216	77.571890	292.7653287	17.11038657	−1.05637889	−0.18194654	36.96614286	94.29385714
EFC	216	117953844.9	$1.32202e^{16}$	114979299.3	1.692156597	2.860351747	6043879.815	609101121.8
CO_2	216	38.98946831	1919.918109	43.81687014	1.524891179	2.320021601	0.289074508	208.0670137
FDI	216	6432533692	$1.28513e^{20}$	1133636364	3.949381262	19.10888326	4451297.031	79094535783
GDP	216	$2.38135e^{11}$	$5.74479e^{22}$	$2.39683e^{11}$	1.584277194	3.1030842	4981659930	$1.17893e^{12}$
GOEX	216	25458500333	$7.66684e^{20}$	27689065485	1.221700036	0.649999982	111862553.8	$1.09716e^{11}$
POP	216	62491225.49	$5.75599e^{15}$	75868260.79	1.594965308	1.719631754	333345	281190067

Note: N = 216 country-year observations, comprising nine ASEAN countries over the period 2000–2023. Ecological Footprint (EFC) represents the national total EFC of consumption measured in global hectares (gha), while CO_2 represents national territorial fossil CO_2 measured in million tonnes of carbon per year (MtC/year). The descriptive statistics are reported in the original measurement units before logarithmic transformation. All descriptive statistics were recalculated from the cleaned analytical dataset after excluding embedded summary rows and non-analytical records. Variance is calculated using the sample variance formula, and kurtosis is reported as excess kurtosis. FDI: Foreign Direct Investment; GDP: Gross Domestic Product; GOEX: Government Expenditure; POP: Population.

Table 3. Matrix correlation

	SDG 12	LnEFC	$LnCO_2$	LnFDI	LnGDP	LnGOEX	LnPOP
SDG 12	1.00000						
LnEFC	−0.000968	1.00000					
$LnCO_2$	0.043840	0.606321	1.000000				
LnFDI	−0.233600	0.496621	0.326151	1.000000			
LnGDP	−0.056693	0.555085	0.647355	0.697723	1.000000		
LnGOEX	−0.213134	0.554345	0.617478	0.680653	0.634009	1.000000	
LnPOP	0.604795	0.320266	0.547993	0.413015	0.540788	0.545515	1.000000

Note: EFC: Ecological Footprint, FDI: Foreign Direct Investment, GDP: Gross Domestic Product, GOEX: Government Expenditure, POP: Population.

4.2 Pre-estimation diagnostic test

Prior to estimating the PQR model, several diagnostic tests are conducted to ensure the appropriateness of the selected econometric framework. One of the most important preliminary procedures in macro-panel analysis is the examination of CSD, which assesses whether shocks occurring in one country are transmitted to other countries within the panel. Considering the high degree of economic integration, trade connectivity, environmental spillovers, and policy interactions among ASEAN countries, the presence of CSD is a plausible characteristic of the dataset.

To evaluate this issue, three complementary tests are employed, namely the Breusch–Pagan LM test, the Pesaran Scaled LM test, and the Pesaran CD test. The use of multiple testing approaches enhances the robustness of the diagnostic process and provides more reliable evidence regarding the existence of interdependencies across cross-sectional units. The results of these tests are reported in Table 4.

All variables consistently reject the null hypothesis of cross-sectional independence across the three testing procedures. These results indicate that shocks and disturbances may be correlated across ASEAN countries, potentially reflecting regional economic integration, common environmental pressures, and shared macroeconomic developments. This finding has important implications for the subsequent estimation because conventional fixed-effects and PQR models do not automatically eliminate the consequences of CSD. Accordingly, the estimated coefficients and their statistical significance should be interpreted with caution unless the estimation procedure or additional robustness analyses adequately address common shocks and cross-country interdependence.

The presence of CSD is particularly relevant for SCP because environmental pressures often exhibit transboundary characteristics. Changes in ecological conditions, CO_2, production structures, or economic performance in one country may indirectly influence neighboring countries

through trade networks, production linkages, technological diffusion, and regional environmental interactions. Consequently, the observed dependence across countries highlights the importance of employing estimation procedures that explicitly account for such interrelationships.

From an econometric perspective, the detection of CSD implies that conventional first-generation panel techniques may produce biased or inconsistent results if cross-country interactions are ignored. Therefore, the findings reported in Table 4 provide empirical justification for proceeding with second-generation panel diagnostic procedures, particularly the CIPS unit root test, which is specifically designed to accommodate CSD. This step ensures that the subsequent empirical analysis is based on estimation techniques that are consistent with the underlying characteristics of the dataset.

The CSD tests reported in Table 4 indicate statistically significant interdependence among the ASEAN countries. This finding suggests that country-level observations may be exposed to common regional and global shocks, as well as spillovers transmitted through trade, production networks, and environmental interactions. These results have important implications for the interpretation of the subsequent regression estimates. In particular, the presence of CSD means that conventional fixed-effects and PQR estimators cannot automatically be assumed to provide valid statistical inference. Although the CIPS test accommodates CSD in the panel unit-root analysis, it does not, by itself, eliminate common shocks or correlated disturbances from the main regression models. Therefore, the baseline estimates should be assessed alongside additional specifications that account for common time shocks, and the inference procedures used for the fixed-effects and PQR models should be explicitly documented.

Table 4. Cross-sectional dependency (CSD) test

Variables	Breusch-Pagan LM	Pesaran Scaled LM	Pesaran CD
SDG 12	256.5836***	25.99603***	5.394734***
LnEFC	593.4519***	65.69633***	24.01465***
$LnCO_2$	719.2900***	80.52650***	26.76019***
LnFDI	178.1854***	16.75672***	9.496481***
LnGDP	662.6862***	73.85568***	22.87036***
LnGOEX	789.7498***	88.83026***	28.07256***
LnPOP	844.0733***	95.23235***	29.05026***

Note: Significance codes: *** <0.01; ** <0.05; * <0.10. LM: Lagrange Multiplier; EFC: Ecological Footprint; FDI: Foreign Direct Investment; GDP: Gross Domestic Product; GOEX: Government Expenditure; POP: Population.

Following the identification of CSD, the next diagnostic procedure involves examining the stationarity properties of the variables. Since the presence of CSD has been confirmed in the previous analysis, the use of second-generation panel unit root tests becomes necessary to obtain reliable results. Accordingly, this study employs the CIPS unit root test, which explicitly accounts for CSD among countries and is therefore more suitable for macro-panel datasets such as ASEAN economies.

The CIPS test is conducted under three alternative specifications, namely no trend, constant, and constant with trend. Employing multiple specifications allows for a more comprehensive assessment of the stochastic properties of the variables and reduces the possibility of biased conclusions arising from model specification choices. The results of the CIPS unit root test are presented in Table 5.

The stationarity properties vary across variables and model specifications. Several variables exhibit stationarity under the constant and constant-with-trend specifications, while others remain non-stationary under certain assumptions. These mixed outcomes indicate that the variables possess different stochastic characteristics and adjustment dynamics over time, which is a common feature of macroeconomic, environmental, and demographic indicators observed across countries with diverse development trajectories.

The findings further suggest that the inclusion of deterministic components, particularly trend effects, improves the stationarity behavior of several variables. This outcome reflects the existence of long-run structural movements in sustainability, environmental, and economic indicators throughout the study period. Given the substantial economic transformation, environmental policy evolution, and sustainability initiatives undertaken by ASEAN countries between 2000 and 2023, the presence of trend-related dynamics is consistent with the underlying characteristics of the dataset.

The CIPS unit root test results reported in Table 5 indicate that the stationarity properties of the variables vary across alternative deterministic specifications. Several variables reject the unit-root null hypothesis under the constant-and-trend specification, whereas some variables remain non-stationary under specifications without a trend or with a constant only. These findings suggest that the inference regarding stationarity is sensitive to the deterministic components included in the test. Accordingly, the results should not be interpreted as conclusive evidence that all variables are stationary in levels. The integration properties of the variables are important for the subsequent fixed-effects and PQR estimations because regressions involving non-stationary variables may produce misleading statistical relationships if the relevant long-run properties are not established. Therefore, the baseline estimates are interpreted cautiously, and the possibility of common time trends and non-stationarity is acknowledged when assessing the empirical relationships between environmental pressures and SDG 12 performance.

An important methodological consideration is that the unit root test results do not, by themselves, establish whether the variables used in the level regressions share a valid long-run relationship. In particular, the presence of non-stationary variables raises the possibility of spurious regression if common stochastic trends are not adequately accounted for. The baseline fixed-effects and PQR estimates should therefore be interpreted as conditional empirical associations rather than definitive evidence of long-run equilibrium relationships. In the absence of additional cointegration or dynamic-model tests, the possibility that non-stationarity affects the estimates remains a limitation of the analysis.

An additional methodological consideration concerns the sensitivity of the estimated relationships to common time-

specific shocks. Although year fixed effects may help account for temporal factors affecting all countries simultaneously, a year-dummy QREG specification is not retained as a formal robustness test in this study. This decision reflects the need to ensure that any supplementary quantile estimates are generated using exactly the same estimation settings as the baseline specification. Since this requirement cannot be verified for the supplementary estimates, the study does not make a formal robustness claim regarding the inclusion of year fixed effects. Consequently, the baseline QREG results should be interpreted as conditional associations under the specified estimation framework, while their sensitivity to common year-specific shocks remains an issue for further empirical investigation.

Table 5. Cross-sectionally Augmented IPS (CIPS) unit root test results

Variables	No Trend	Constant	Constant and Trend
SDG 12	−1.54875	−1.90675	−2.36367**
LnEFC	−0.49773	−1.63530	−2.15417**
$LnCO_2$	−0.04303	−2.38416**	−2.36108**
LnFDI	−2.33903**	−2.81250***	−3.47236***
LnGDP	−0.93493	−1.92180	−2.46083**
LnGOEX	−1.12694	−2.41244**	−3.33543***
LnPOP	−0.69764	−1.37462	−2.13015**

Note: Significance codes: *** <0.01; ** <0.05; * <0.10. EFC: Ecological Footprint, FDI: Foreign Direct Investment, GDP: Gross Domestic Product, GOEX: Government Expenditure, POP: Population.

Following the examination of stationarity properties, the next step involves identifying the most appropriate baseline panel specification prior to estimating the PQR model. Model specification testing is essential to account for country-specific heterogeneity and to ensure that the estimated relationships are not biased by unobserved characteristics across ASEAN countries. Based on the specification procedures, the FEM is selected as the preferred baseline framework, and the corresponding estimation results are reported in Table 6.

Table 6. Regression results for fixed effect model (FEM)

Variables	(I)	(II)	(III)
LnEFC	2.498839***		1.830529***
	(0.466188)		(0.405606)
$LnCO_2$	−1.51300***	−0.005583	
	(0.544805)	(0.496462)	
LnFDI	−0.549883***	−0.800100***	−0.571981***
	(0.168865)	(0.172668)	(0.171352)
LnGDP	−19.76774***	−19.55145***	−19.97287***
	(0.632555)	(0.671655)	(0.638190)
LnGOEX	5.939009***	6.082974***	5.329642***
	(0.506176)	(0.537803)	(0.463378)
LnPOP	14.94379***	14.74552***	14.60318***
	(0.247615)	(0.260501)	(0.218518)
Constant	161.6844***	202.6498***	195.1169***
	(12.87170)	(11.01987)	(4.628360)
R-squared	0.968999	0.964737	0.967855
Adjusted-R squared	0.968109	0.963897	0.967089
F-statistic	1088.772	1149.045	1264.563
(p-value)	0.000000	0.000000	0.000000
Obs	216	216	216

Note: Model (I) represents the full baseline specification including both LnEFC and $LnCO_2$. Model (II) excludes LnEFC to isolate the effect of $LnCO_2$, while Model (III) excludes $LnCO_2$ to isolate the effect of LnEFC. Two-way fixed-effects estimates are reported. Conventional ordinary standard errors generated by EViews are presented in parentheses. The specifications include cross-section and period fixed effects, with no GLS weighting applied. The cross-sectional dependence (CSD) tests reported in Table 4 indicate significant cross-country interdependence. Accordingly, the reported standard errors and statistical significance levels are conventional and are not adjusted to account for residual CSD. The significance levels should therefore be interpreted with caution. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively, based on the conventional EViews standard errors. EFC: Ecological Footprint; FDI: Foreign Direct Investment; GDP: Gross Domestic Product; GOEX: Government Expenditure; POP: Population.

To assess the robustness of the baseline relationship, three model specifications are estimated. The first specification includes the complete set of explanatory and control variables. The second and third specifications are subsequently estimated by alternately excluding the two main explanatory variables, thereby allowing the consistency of the estimated coefficients to be evaluated across different model structures. This approach provides a preliminary assessment of the stability of the empirical relationships before proceeding to the quantile-based estimations.

The results indicate that the principal explanatory variables maintain statistical significance across the estimated specifications. Moreover, the signs of the coefficients remain generally stable, suggesting that the relationship between environmental pressures and SCP is not sensitive to alternative model configurations. The consistency of the estimated coefficients across specifications provides initial evidence regarding the robustness of the baseline model and supports the reliability of the subsequent distributional analysis.

Regarding the control variables, the estimation results reveal that the selected controls contribute significantly to explaining variations in SCP performance across ASEAN countries. Their statistical significance confirms that differences in economic conditions, public sector involvement, investment activities, and demographic characteristics constitute important background factors that should be controlled for when assessing the effects of environmental pressures. The inclusion of these controls therefore helps isolate the independent contribution of the primary explanatory variables while reducing the risk of omitted-variable bias.

The goodness-of-fit indicators further demonstrate that the estimated models possess strong explanatory power. The relatively high explanatory capacity suggests that the combination of environmental and control variables is able to account for a substantial proportion of the variation in SDG 12 performance across the sample countries. In addition, the consistency of the explanatory power across the three specifications indicates that the overall model structure remains stable despite changes in the inclusion of the primary explanatory variables.

The estimation results in Table 6 indicate that the explanatory variables are jointly statistically significant across the three model specifications, as reflected in the reported F-

statistics. The coefficient estimates also show relatively consistent patterns across specifications, particularly for FDI, economic development, GOEX, and POP. Nevertheless, these findings should be interpreted with caution. The CSD tests reported in Table 4 reveal significant interdependence among ASEAN countries, while the fixed-effects estimates in Table 6 are based on conventional ordinary standard errors generated by EViews. Although the specifications include both cross-section and period fixed effects, these covariance settings do not ensure standard errors that are robust to residual CSD. Therefore, the reported significance levels should be regarded as conventional statistical inference rather than dependence-robust evidence. The results provide preliminary evidence of conditional associations between the explanatory variables and SDG 12 performance, but their statistical precision may be affected by cross-country dependence. Accordingly, the coefficient estimates are interpreted cautiously and should not be regarded as definitive evidence of causal effects.

The relatively large negative coefficient of LnGDP warrants further investigation. Across the three fixed-effects specifications, the estimated coefficient ranges from −19.55145 to −19.97287. Although the coefficient remains relatively stable across these specifications, this stability alone does not establish that its magnitude is economically meaningful or that the model is correctly specified. The result may reflect the measurement scale and price basis of the economic variables, common time trends, or multicollinearity among GDP, POP, and GOEX. Therefore, the coefficient should be interpreted cautiously pending further diagnostic and robustness analyses. In particular, the measurement basis of GDP, GOEX, and FDI should be verified, and the sensitivity of the estimates to multicollinearity and the inclusion of year fixed effects should be assessed.

4.3 Estimation results of pooled quantile regression

After establishing the suitability of the dataset through a series of diagnostic and specification tests, the PQR framework is employed to investigate the heterogeneous effects of environmental pressures on SCP across ASEAN countries. Unlike conventional mean-based estimators, the PQR approach allows the effects of explanatory variables to be examined across different points of the conditional distribution of SDG 12 performance. Consequently, the method provides a more comprehensive understanding of whether the impacts of environmental pressures vary among countries exhibiting low, medium, and high levels of SCP achievement.

Table 7 presents the estimation results for quantiles ranging from the 10th to the 90th percentile. The findings reveal substantial heterogeneity in the estimated coefficients across quantiles, indicating that the determinants of SCP do not exert uniform effects throughout the distribution. Such variation confirms the suitability of the quantile-based framework and suggests that countries positioned at different levels of SDG 12 performance may respond differently to environmental and economic conditions.

Table 7. Estimating results from the pooled quantile regression (PQR) framework

	LnEFC	$LnCO_2$	LnFDI	LnGDP	LnGOEX	LnPOP
0.1QR	3.298803	−0.184075	−0.745609**	−16.97841***	3.316056***	13.78620***
	(3.253432)	(3.845235)	(0.294588)	(3.064849)	(0.974638)	(0.663153)
0.2QR	1.133634	−0.109904	−0.792121**	−20.15781***	5.742014***	14.95064***
	(0.758025)	(0.943310)	(0.313799)	(0.654227)	(0.764774)	(0.392258)
0.3QR	2.216775**	−1.235930	−0.820456***	−19.34547***	5.601606***	14.89142***
	(1.075891)	(1.244343)	(0.223842)	(0.928502)	(0.559115)	(0.307496)
0.4QR	1.833182***	−1.288130*	−0.724029***	−19.30872***	5.663031***	14.97933***
	(0.649223)	(0.661754)	(0.208438)	(0.643397)	(0.504985)	(0.322167)
0.5QR	1.948484***	−1.541278**	−0.625324***	−19.44227***	5.890760***	15.04040***
	(0.641353)	(0.636954)	(0.210394)	(0.693014)	(0.537199)	(0.345341)
0.6QR	2.524497***	−2.026551***	−0.497553**	−20.14739***	6.431469***	15.16624***
	(0.552158)	(0.487822)	(0.203190)	(0.735634)	(0.515363)	(0.400986)
0.7QR	3.212604***	−1.965364***	−0.407685*	−20.96383***	6.591370***	15.23355***
	(0.558373)	(0.529677)	(0.217156)	(0.767510)	(0.507676)	(0.359732)
0.8QR	3.454891***	−2.052512***	−0.354003	−20.85559***	6.546667***	15.24674***
	(0.590224)	(0.525373)	(0.229960)	(0.825648)	(0.535424)	(0.344103)
0.9QR	3.318494**	−2.775285***	0.117772	−19.88386***	6.612139***	14.74859***
	(1.393259)	(1.383259)	(0.193132)	(2.460969)	(0.894599)	(0.726451)

Note: Estimates are obtained using the EViews quantile regression (QREG) procedure based on the least absolute deviations (LAD) approach across the 10th to 90th quantiles. Huber Sandwich standard errors are reported in parentheses. Sparsity is estimated using the kernel method with the Hall–Sheather bandwidth, a size parameter of 0.05, the Rankit (Cleveland) quantile method, and the Epanechnikov kernel. No bootstrap procedure is employed. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively, based on the corresponding EViews p-values. EFC: Ecological Footprint; FDI: Foreign Direct Investment; GDP: Gross Domestic Product; GOEX: Government Expenditure; POP: Population.

Regarding the primary explanatory variables, EFC exhibits a generally positive and statistically significant effect across most quantiles of the SDG 12 distribution. Moreover, the magnitude of the estimated coefficient tends to become larger at the upper quantiles, indicating increasing sensitivity among countries with relatively higher levels of SCP performance. The persistence of statistical significance across a wide range of quantiles demonstrates that ecological conditions remain closely associated with sustainability outcomes throughout the ASEAN region.

The positive association between EFC and SDG 12 performance should be interpreted cautiously. Although the result may indicate that countries with higher EFCs also exhibit higher measured SDG 12 scores, it does not establish that greater ecological pressure improves SCP. The relationship may reflect differences in economic development, resource-use patterns, or measurement characteristics across countries. Consequently, the coefficient should not be interpreted as evidence of a beneficial environmental effect. Its robustness needs to be assessed using alternative indicators

that more directly capture material use, resource productivity, or circular-economy performance.

Similarly, CO_2 displays significant effects across several quantiles, although the magnitude and statistical significance vary throughout the distribution. Compared with EFC, the estimated coefficients for CO_2 exhibit greater fluctuations between lower and upper quantiles, suggesting the presence of heterogeneous distributional effects. These results indicate that the influence of emission-related environmental pressures differs according to the level of SCP achieved by individual countries.

The estimation results also show that the control variables remain relevant throughout the quantile distribution. FDI, economic development, GOEX, and POP maintain statistical significance across a substantial number of quantiles, confirming their role as important background factors influencing sustainability performance. Their inclusion strengthens the robustness of the model by ensuring that the estimated effects of environmental pressures are evaluated while controlling for differences in economic structure, public sector involvement, investment activities, and demographic characteristics across ASEAN countries.

Another notable feature of the results is the variation in coefficient magnitudes across the conditional distribution of SDG 12. Several variables exhibit stronger effects at either the lower or upper quantiles, highlighting the presence of asymmetric responses among countries with different sustainability performance levels. This pattern suggests that the determinants of SCP may operate through different mechanisms depending on a country's position within the sustainability distribution.

The results provide strong empirical evidence that the relationship between environmental pressures and SCP is heterogeneous rather than uniform. The observed differences across quantiles indicate that average-effect estimators may conceal important distributional dynamics. Therefore, the PQR framework offers a more nuanced perspective on the determinants of SDG 12 achievement by capturing variations across countries characterized by different levels of sustainability performance.

To complement the regression estimates presented in Table 7, Figure 1 illustrates the distributional behavior of the estimated coefficients across the quantile spectrum. The graphical representation provides a visual assessment of coefficient stability, directional consistency, and the extent of heterogeneity among the explanatory variables. In addition, the confidence intervals surrounding the estimated coefficients facilitate the evaluation of statistical significance and uncertainty across quantiles.

The figure confirms the heterogeneous patterns observed in the tabulated results. Several coefficients exhibit noticeable variations across the conditional distribution of SDG 12, indicating that their effects are not constant among countries with different levels of SCP performance. In contrast, some variables display relatively stable coefficient trajectories throughout the quantiles, suggesting a more consistent relationship with sustainability outcomes. These differences further support the argument that distributional analysis is necessary to capture the complexity of sustainability dynamics within ASEAN countries.

Furthermore, the graphical evidence highlights that the estimated effects of the primary explanatory variables evolve differently across the quantile spectrum. The trajectories of EFC and CO_2 demonstrate varying degrees of responsiveness as countries move from lower to higher levels of SDG 12 performance. Meanwhile, the control variables generally exhibit smoother patterns, reinforcing their role as background determinants rather than the primary focus of the analysis. Taken together, Figure 1 visually corroborates the findings reported in Table 7 and provides additional evidence regarding the heterogeneous nature of the relationships captured by the PQR framework.

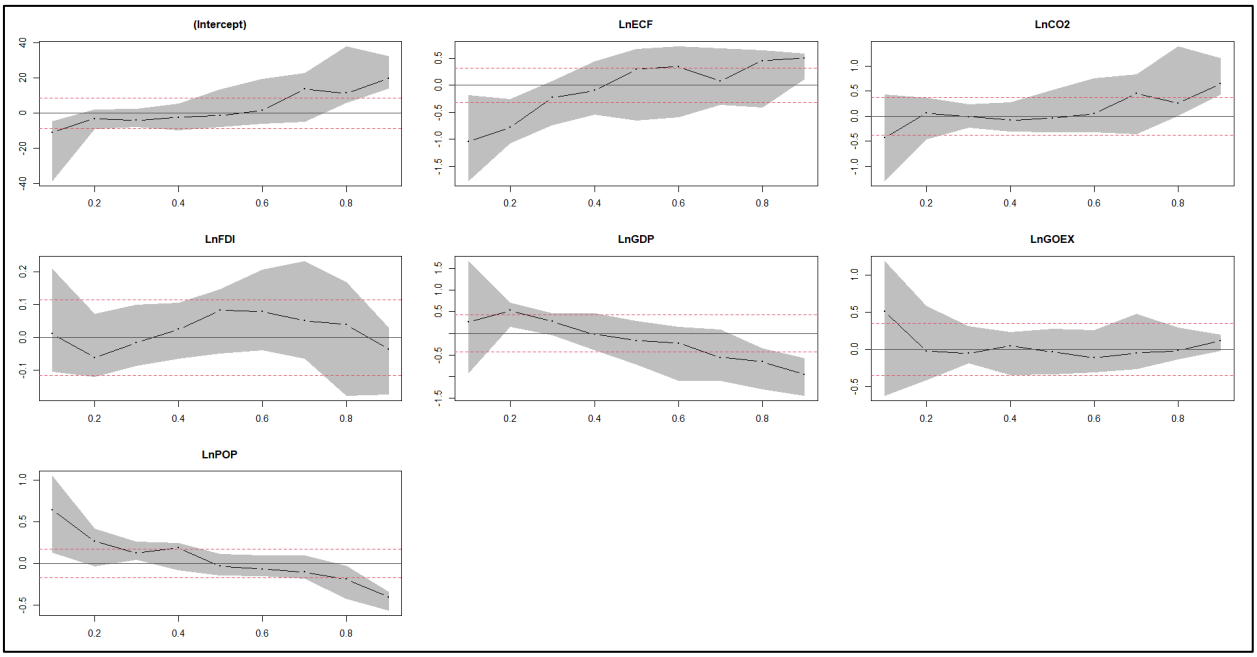


Figure 1. Pooled quantile regression (PQR) framework

Following the baseline and robustness analyses, this study further explores whether the effects of environmental pressures on SCP differ across groups of countries within ASEAN. Based on the classification commonly adopted from Tang, ASEAN countries are divided into two groups: leading economies and non-leading economies. In this study, the

leading economies consist of Indonesia, Malaysia, Thailand, Singapore, and Vietnam, while the non-leading economies include Brunei Darussalam, Cambodia, Laos, and the Philippines [72, 73]. This classification reflects differences in economic development, institutional capacity, industrial structure, and progress in sustainability transitions. By separating the sample into these two groups, the analysis aims to identify whether the relationship between environmental pressures and SCP exhibits heterogeneous patterns across different stages of economic and sustainability development.

Table 8 reports the sub-sample PQR estimates for both leading and non-leading ASEAN economies across the lower, median, and upper quantiles of SDG 12 performance. The results reveal notable differences in the estimated coefficients between the two groups, suggesting that the determinants of SCP are not uniform across ASEAN countries. These findings provide preliminary evidence that the influence of environmental pressures may vary according to the level of economic development and sustainability readiness.

For the leading economies, the estimated coefficients remain relatively stable across quantiles, indicating a more consistent relationship between environmental pressures and SCP performance. The persistence of statistical significance across several quantiles suggests that environmental factors continue to play an important role throughout different levels of sustainability achievement. Such consistency may reflect the more established institutional frameworks, stronger environmental governance mechanisms, and greater policy coordination observed among the leading ASEAN economies.

In contrast, the non-leading economies exhibit greater variability in both coefficient magnitudes and significance levels across quantiles. The results suggest that the effects of environmental pressures are more heterogeneous within this group, potentially reflecting differences in economic structures, resource dependence, technological capacities, and environmental management systems. The wider variation across quantiles indicates that sustainability outcomes in these countries may be more sensitive to changes in environmental and developmental conditions.

The control variables continue to perform their intended role throughout the sub-sample estimations. Their inclusion ensures that the estimated effects of the primary explanatory variables are not confounded by differences in economic scale, investment activity, public sector involvement, or demographic conditions. Although some control variables remain significant across particular quantiles, their primary purpose in this framework is to account for background structural differences between countries rather than serve as the main focus of the analysis.

The sub-sample analysis provides suggestive evidence of regional heterogeneity within ASEAN. The differences observed between the leading and non-leading country groups indicate that the association between environmental pressures and SDG 12 performance may vary according to country-specific economic and institutional conditions. However, given the small number of countries in the non-leading group, these differences should be interpreted as indicative rather than conclusive evidence of systematic regional heterogeneity. The findings therefore highlight the potential importance of country-group characteristics while recognizing the limitations associated with the small Group 2 sample. Consequently, the findings highlight the importance of considering country-group characteristics when evaluating the determinants of SCP and further justify the use of distribution-sensitive estimation approaches such as the PQR framework.

However, the sub-sample estimates for the non-leading economies should be interpreted with caution because Group 2 consists of only four countries, namely Brunei, Cambodia, Laos, and the Philippines. Although the panel structure provides repeated observations over time, the small number of cross-sectional units may limit the precision and external generalizability of the group-specific quantile estimates. Therefore, the results for Group 2 should be regarded as indicative evidence of distributional patterns within the observed countries rather than as definitive estimates for non-leading ASEAN economies as a whole. The possibility of sampling-related uncertainty should also be considered when comparing the estimated coefficients across the two country groups.

Table 8. Regional heterogeneity analysis: sub-sample pooled quantile regression (PQR) estimates

Variable	Group 1 (Leading Economies)			Group 2 (Non-Leading Economies)		
	Q25	Q50	Q75	Q25	Q50	Q75
LnEFC	3.610867***	2.892075***	2.762279***	−9.255225***	−8.175546***	−7.014993***
	(0.430541)	(0.526873)	(0.446950)	(0.735752)	(1.414680)	(2.390667)
$LnCO_2$	5.234774***	3.584716***	4.033056***	−0.161077	0.103432	−0.038579
	(1.300211)	(0.847071)	(0.845763)	(0.459991)	(0.689829)	(0.978084)
LnFDI	-0.221085	-0.097430	−0.336099	0.200858**	0.126275	0.083259
	(0.165974)	(0.218273)	(0.335690)	(0.098539)	(0.124706)	(0.153006)
LnGDP	−12.40519***	−12.99983***	−11.79351***	4.133828***	0.556404	−1.850931
	(0.948488)	(0.959976)	(0.994523)	(1.490903)	(2.466491)	(3.924342)
LnGOEX	0.675377	0.866398	−0.130082	−2.192476***	−0.680551	0.447290
	(0.578697)	(0.732204)	(0.546717)	(0.747751)	(0.971750)	(0.887496)
LnPOP	10.15896***	11.38401***	11.02194***	6.718061***	7.499279***	7.877096***
	(0.848333)	(0.514618)	(0.394317)	(0.426072)	(0.610877)	(1.653102)

Note: Estimates are obtained using the EViews quantile regression (QREG) procedure based on the least absolute deviations (LAD) approach for the respective country subsamples. Huber Sandwich standard errors are reported in parentheses. Sparsity is estimated using the kernel method with the Hall–Sheather bandwidth, a size parameter of 0.05, the Rankit (Cleveland) quantile method, and the Epanechnikov kernel. No bootstrap procedure is employed. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively, based on the corresponding EViews p-values. Group 1: Indonesia, Malaysia, Thailand, Singapore, and Vietnam; Group 2: Brunei Darussalam, Cambodia, Laos, and the Philippines. EFC: Ecological Footprint; FDI: Foreign Direct Investment; GDP: Gross Domestic Product; GOEX: Government Expenditure; POP: Population.

The regional heterogeneity analysis provides preliminary evidence that the associations between environmental pressures and SDG 12 performance may differ between leading and non-leading ASEAN economies. However, the

subgroup estimates require cautious interpretation because Group 2 comprises only four countries: Brunei Darussalam, Cambodia, Lao PDR, and the Philippines. Although the panel structure provides repeated observations over time, the small number of cross-sectional units limits the strength of statistical inference and the generalizability of the estimated group-specific relationships. Accordingly, differences in coefficient magnitudes and statistical significance across the two groups should not, by themselves, be interpreted as conclusive evidence of systematic differences between leading and non-leading economies. Stronger assessment requires additional sensitivity analysis and, where feasible, formal tests of group differences using the full sample. The subgroup results are therefore treated as exploratory evidence rather than definitive estimates of regional heterogeneity.

The observed heterogeneity across ASEAN countries may reflect differences not only in their levels of SDG 12 performance but also in the broader economic and institutional systems in which environmental pressures operate. Institutional quality, industrial structure, energy composition, and participation in global value chains may be relevant dimensions for understanding these differences. For example, countries with different institutional capacities may vary in their ability to implement sustainable production policies, while differences in manufacturing structures and energy mixes may shape the relationship between CO_2, EFC, and SDG 12 performance. Similarly, participation in global value chains may influence production specialisation and the distribution of resource-intensive activities across countries. However, these potential explanations are not directly tested in the present analysis because the corresponding system-level variables are not included in the estimated models. Therefore, the group-specific results should be interpreted as evidence of differences in conditional associations rather than as confirmation of the institutional, industrial, energy-related, or trade-related mechanisms underlying those differences.

To complement the sub-sample regression estimates, Figure 2 illustrates the coefficient trajectories across quantiles for both leading and non-leading ASEAN economies. The graphical representation provides a visual comparison of the distributional effects and allows the stability of the estimated coefficients to be assessed across different levels of SCP performance. Furthermore, the confidence intervals surrounding the estimated coefficients offer additional information regarding the precision and significance of the quantile estimates.

The figure clearly demonstrates that the coefficient paths differ between the two country groups. For the leading economies, several variables exhibit relatively smoother and more stable trajectories across the quantile distribution, indicating a more consistent relationship with SDG 12 performance. By contrast, the non-leading economies display greater fluctuations across quantiles, reflecting higher sensitivity to changes in environmental and economic conditions.

The results provide evidence of regional heterogeneity within ASEAN by highlighting differences in both the magnitude and distribution of the estimated effects across country groups. The graphical results support the argument that sustainability dynamics vary according to development stages and institutional capacities, thereby emphasizing the importance of considering group-specific characteristics when evaluating the determinants of SCP performance across ASEAN countries.

4.4 Discussion

The findings of this study provide important evidence regarding the role of environmental pressures in shaping SCP performance across ASEAN countries. Consistent with the ecological modernization perspective, environmental conditions are not merely outcomes of economic activities but also constitute important determinants of sustainability transitions. The results suggest that environmental pressures influence the ability of countries to achieve SDG 12 through their impacts on resource efficiency, production structures, and long-term environmental resilience. Sustainability outcomes have been found to depend on the extent to which ecological considerations are integrated into economic systems [35, 36].

One of the most notable findings concerns the positive relationship between EFC and SDG 12 performance. At first glance, this result may appear counterintuitive because EFC is commonly associated with environmental degradation. A larger EFC may also reflect higher levels of economic activity, industrial development, and production capacity that enable countries to invest in sustainability-oriented technologies, waste management systems, and resource-efficiency initiatives. Consequently, countries with greater ecological utilization may simultaneously possess stronger institutional and economic capacities to implement SCP programs.

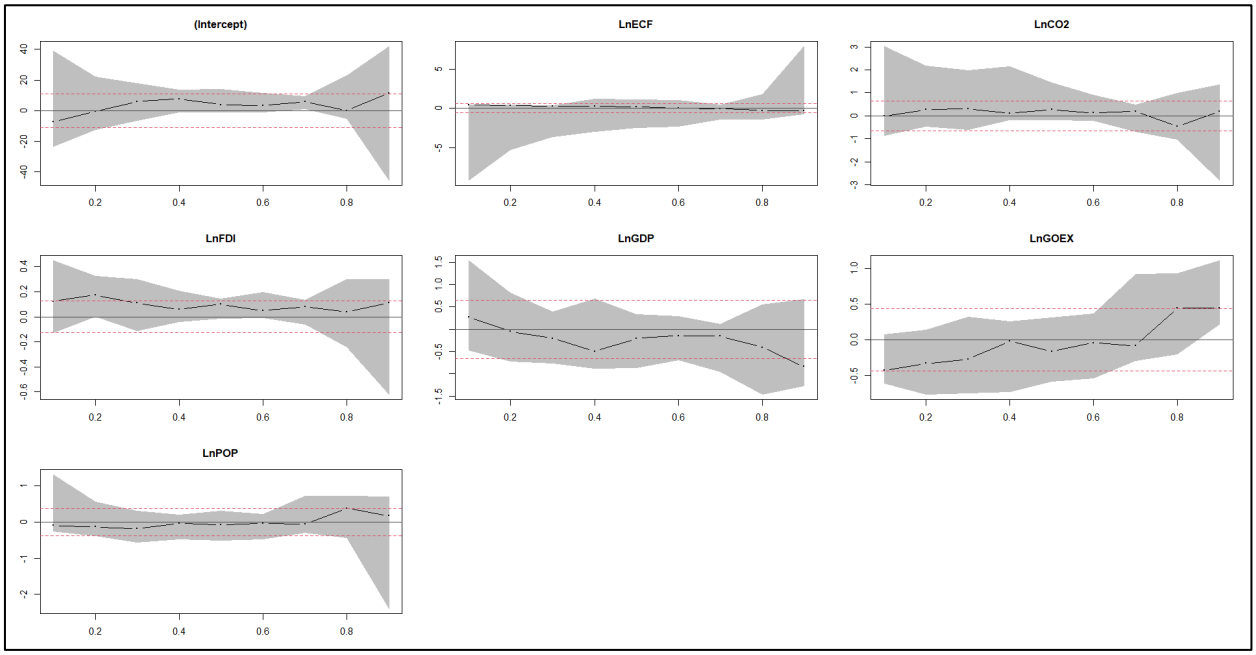
This interpretation partially differs from the conventional environmental degradation literature. Increasing EFCs have been associated with unsustainable resource utilization and growing environmental pressure [40-42]. Excessive EFCs have been associated with resource inefficiencies and ecological overexploitation [44, 45]. Nevertheless, the present findings suggest that the relationship between EFC and sustainability outcomes may be more complex in developing regions. Rather than representing environmental deterioration alone, EFC may also capture the scale of economic systems capable of supporting sustainability investments and institutional adaptation.

The heterogeneous effects observed across quantiles further reinforce this interpretation. Countries with relatively higher SDG 12 performance appear to derive stronger sustainability gains despite experiencing greater ecological pressures. This outcome is consistent with the Environmental Kuznets Curve hypothesis, which suggests that countries at more advanced stages of development are generally better positioned to transform environmental challenges into opportunities for technological upgrading and sustainability improvements [60, 61]. Therefore, environmental pressure does not necessarily translate into weaker sustainability performance when supported by effective institutions and resource management strategies.

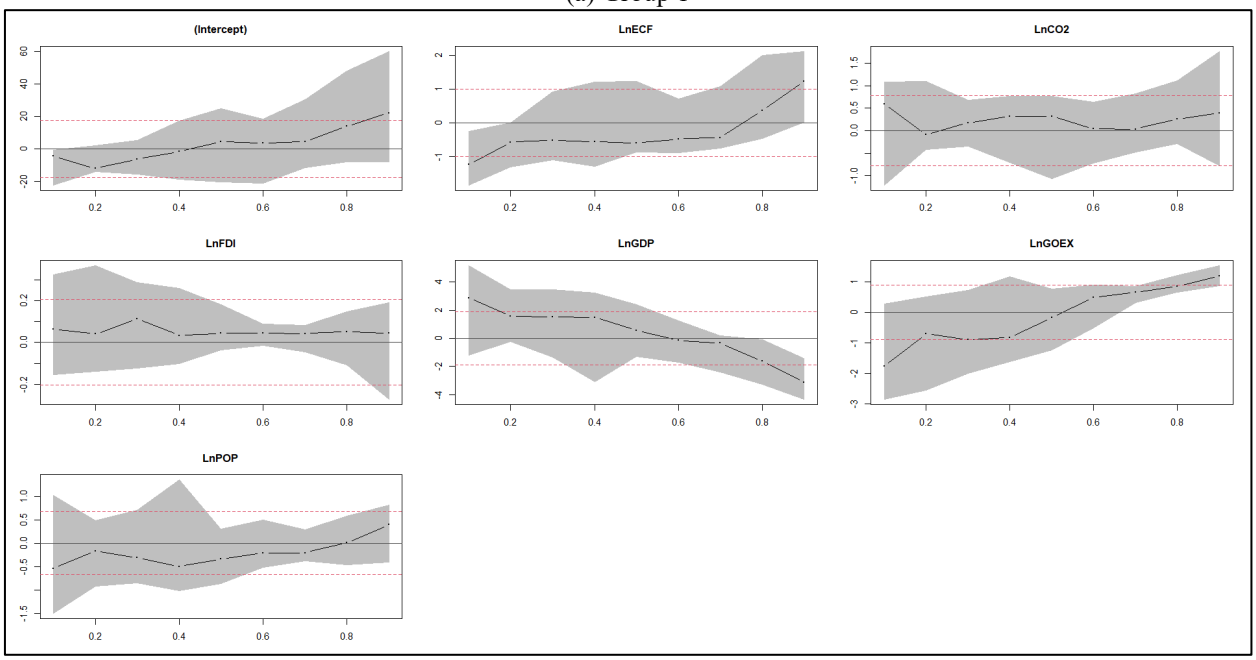
In contrast, CO_2 exhibits an adverse relationship with SCP performance. This finding supports the theoretical argument that carbon-intensive development pathways undermine sustainability objectives by increasing dependence on fossil fuels, encouraging inefficient production systems, and generating significant environmental externalities. CO_2 has been associated with unsustainable economic structures characterized by high environmental costs and low resource efficiency [23, 48].

The findings also corroborate previous empirical studies emphasizing the detrimental consequences of carbon-intensive growth. Increasing emissions have been associated with environmental degradation and declining sustainability

performance [49-51]. Emission-intensive production systems have been associated with inefficient technologies and reliance on non-renewable energy sources, limiting economies' capacity to transition towards sustainable production structures [52, 53]. The evidence from ASEAN confirms that countries characterized by higher CO_2 face greater challenges in advancing responsible consumption and production practices.



(a) Group 1



(b) Group 2

Figure 2. Regional heterogeneity analysis

Another important implication of the findings concerns the distributional heterogeneity identified across quantiles. The varying effects observed throughout the SDG 12 distribution indicate that sustainability transitions are not uniform across ASEAN countries. Differences in institutional quality, technological capabilities, and environmental governance have been found to significantly influence sustainability outcomes [62, 63]. As a result, countries with similar environmental conditions may experience different sustainability trajectories depending on their capacity to manage environmental pressures effectively.

The regional heterogeneity analysis further strengthens this conclusion. The distinction between leading and non-leading ASEAN economies demonstrates that environmental pressures operate within different economic and institutional contexts. Leading economies generally possess stronger governance structures, higher technological readiness, and more mature sustainability frameworks, allowing them to respond more effectively to environmental challenges. In contrast, non-leading economies often face greater constraints related to financial resources, technological adoption, and environmental management capacity. These differences explain why the relationship between environmental pressures and SDG 12 performance varies across country groups.

The findings also contribute to the emerging literature that views environmental indicators as determinants rather than merely outcomes of sustainable development. Environmental conditions have been found to directly influence the achievement of multiple SDGs through their effects on ecosystem services, resource availability, and long-term economic resilience [57-59]. By placing SDG 12 as the outcome variable, this study extends existing research and provides new evidence regarding the channels through which environmental pressures shape sustainability performance.

Achieving SCP requires more than environmental protection alone. Effective sustainability transitions depend on the ability of countries to improve resource efficiency, reduce carbon-intensive production, strengthen environmental governance, and promote technological innovation. For ASEAN countries, balancing economic development with ecological sustainability remains a critical challenge. Consequently, policies aimed at reducing CO_2, improving environmental efficiency, and enhancing institutional capacity are likely to play a decisive role in accelerating progress toward SDG 12 and broader sustainable development objectives.

5. CONCLUSIONS

This study investigates the effects of environmental pressures on SCP (SDG 12) in nine ASEAN countries over the period 2000–2023 using the PQR framework. The findings reveal that EFC and CO_2 exert significant but heterogeneous effects across different levels of SDG 12 performance. EFC demonstrates a generally positive relationship with SCP, indicating that countries with greater economic and production capacities may simultaneously possess stronger capabilities to implement sustainability-oriented initiatives. In contrast, CO_2 negatively affects SDG 12 performance, suggesting that carbon-intensive development pathways remain a major obstacle to achieving SCP objectives within the ASEAN region.

Furthermore, the quantile-based analysis confirms that the impacts of environmental pressures vary substantially across countries with different sustainability performance levels. The regional heterogeneity analysis also reveals distinct patterns between leading and non-leading ASEAN economies, highlighting the importance of economic development, institutional capacity, and sustainability readiness in shaping environmental outcomes. Overall, the study demonstrates that environmental conditions are not merely outcomes of economic activities but also important determinants of sustainability transitions and progress toward SDG 12. These findings contribute to the growing sustainability literature by providing new evidence on the environmental drivers of SCP in one of the world's most dynamic developing regions.

6. POLICY IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH

6.1 Policy implications

The findings suggest that ASEAN governments should strengthen policies aimed at improving resource efficiency throughout production and consumption systems. Rather than focusing solely on reducing resource use, policymakers should prioritize the transition toward circular economy practices that maximize resource productivity while minimizing waste generation. The adoption of cleaner production technologies, sustainable manufacturing standards, and resource-efficient industrial processes can help reduce ecological pressures without compromising economic competitiveness. Such measures are particularly important for rapidly industrializing economies where resource demand continues to increase alongside economic growth.

A second policy priority involves accelerating decarbonization strategies across key economic sectors. Since CO_2 is found to hinder SCP performance, ASEAN countries should intensify efforts to reduce dependence on fossil fuels and promote low-carbon development pathways. This may include expanding renewable energy deployment, strengthening energy efficiency standards, encouraging green transportation systems, and supporting investments in clean technologies. These initiatives would not only contribute to climate mitigation objectives but also facilitate progress toward SDG 12 by promoting more sustainable production structures.

The results also highlight the importance of differentiated policy approaches across ASEAN countries. Given the heterogeneous effects identified across quantiles and country groups, a uniform regional strategy may not generate optimal outcomes. Leading economies such as Singapore, Malaysia, Thailand, Indonesia, and Vietnam should focus on technological innovation, advanced environmental governance, and sustainable industrial upgrading. Meanwhile, non-leading economies may require greater support in strengthening institutional capacity, improving environmental monitoring systems, and facilitating access to green technologies. Tailoring policy interventions according to country-specific conditions can enhance the effectiveness of sustainability programs throughout the region.

Regional cooperation should also be strengthened to address the transboundary nature of environmental pressures. ASEAN member states can benefit from enhanced collaboration in environmental monitoring, technology transfer, green financing, and sustainable supply chain management. Joint initiatives aimed at reducing emissions, improving resource efficiency, and promoting sustainable production standards would help create a more coordinated regional response to sustainability challenges. Such cooperation is particularly relevant given the strong economic interdependence and environmental spillover effects observed among ASEAN countries.

Finally, policymakers should integrate SDG 12 more explicitly into national development planning frameworks. SCP should not be treated solely as an environmental objective but as a strategic component of long-term economic development. Governments can promote this integration through fiscal incentives for green industries, sustainability-based public procurement systems, environmental education programs, and stronger regulatory frameworks encouraging responsible consumption behavior. By embedding SDG 12 into broader development strategies, ASEAN countries can simultaneously enhance economic resilience, environmental sustainability, and social well-being.

6.2 Interpretation and scope of the policy discussion

The policy implications of this study should be interpreted in light of the estimated associations between environmental

pressures and SDG 12 performance, as well as the observed heterogeneity across countries and quantiles. Rather than adopting a uniform policy approach, ASEAN policymakers should consider differences in national circumstances and the distribution of SCP performance. Countries with relatively low SDG 12 scores may benefit from prioritising basic resource-efficiency measures, improved environmental monitoring, and stronger implementation of sustainable production practices. Countries with relatively high SDG 12 scores may focus on consolidating existing progress through cleaner production technologies, resource-efficient industrial processes, and the integration of sustainability principles into value chains. These priorities represent potential policy directions rather than effects directly established by the estimated coefficients. The findings should therefore be used to inform context-specific policy discussions, not as definitive evidence that particular governance, technological, or industrial interventions will cause improvements in SDG 12 performance. Further research incorporating direct measures of institutional capacity, technological upgrading, and industrial structure would help evaluate these policy channels more rigorously.

6.3 Limitations and future research directions

Despite providing important insights into the relationship between environmental pressures and SCP, this study has several limitations. First, the analysis focuses primarily on EFC and CO_2 as indicators of environmental pressure, while other relevant environmental dimensions such as biodiversity loss, waste generation, renewable energy adoption, and material footprint are not incorporated. Second, the study relies on country-level aggregate data, which may not fully capture subnational variations in sustainability performance and environmental conditions. Third, although the PQR framework effectively identifies heterogeneous effects across quantiles, it does not explicitly examine the causal mechanisms through which environmental pressures influence SDG 12 outcomes.

Fourth, the sub-sample analysis of non-leading ASEAN economies comprises only four countries, which limits the precision and external generalizability of the group-specific quantile estimates. Accordingly, the observed differences between country groups should be interpreted as indicative patterns rather than definitive evidence of systematic heterogeneity. Future research could address this limitation by expanding the country coverage and employing resampling-based inference, such as bootstrap procedures, to assess the robustness of sub-sample quantile estimates.

Fifth, the study relies on the composite SDG 12 score rather than disaggregated indicators of SCP. The composite measure does not allow the analysis to determine whether the estimated associations are primarily related to material use, waste management, resource productivity, or other specific dimensions of SDG 12. Moreover, comparable data for alternative measures—including material footprint, domestic material consumption, waste intensity, energy intensity, and green patents—were not available for the full country-year sample used in this study. Accordingly, the results should not be interpreted as evidence that the identified relationships apply uniformly across all dimensions of SCP. Future research could address this limitation by incorporating disaggregated SDG 12 indicators and alternative measures when sufficiently comparable data become available.

Sixth, the study does not formally establish the sensitivity of the baseline QREG estimates to common year-specific shocks through an additional year-dummy specification. Although such an analysis could provide further insights into the influence of temporal factors, the supplementary estimates are not reported as a robustness test because their estimation settings could not be verified as fully consistent with those applied in the baseline model. Accordingly, the empirical findings should be interpreted within the scope of the reported baseline specifications, and future research may extend the analysis by examining the sensitivity of quantile estimates to common time-specific effects using fully harmonized estimation procedures.

Future studies may extend the present analysis by incorporating a broader set of environmental, technological, and institutional indicators to provide a more comprehensive understanding of SCP dynamics. Researchers may also explore the mediating or moderating roles of variables such as renewable energy transition, green innovation, environmental governance, digitalization, or circular economy development in shaping SDG 12 performance. In addition, the application of advanced methodologies, including spatial econometric models, dynamic panel approaches, machine learning techniques, or causal inference frameworks, could offer deeper insights into the complex interactions between environmental pressures and sustainability outcomes. Expanding the analysis to other regional blocs or conducting cross-regional comparisons would further enhance the generalizability of the findings and contribute to the broader sustainability literature.

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AI STATEMENT

Generative artificial intelligence tools were used during the manuscript preparation process to assist with language polishing, grammar checking, formatting, and non-substantive editorial improvements. These tools were not intended to replace the authors' intellectual contributions, scientific judgment, or responsibility for the research.

The authors independently assume responsibility for the research design, data sources, empirical analysis, interpretation of findings, theoretical arguments, policy implications, and selection and verification of references. All empirical results and citations have been reviewed and validated by the authors against the underlying data and original sources. The authors take full responsibility for the accuracy, originality, validity, and integrity of the manuscript and confirm that the final submitted version has been critically reviewed and approved by all authors.

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