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Natural Resource Rents, Renewable Energy Transition, and Carbon Footprint in ASEAN Economies: Testing the Environmental Kuznets Curve

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ABSTRACT

Environmental degradation has turned into a significant policy issue in ASEAN economies since the rapid economic growth, natural resource exploitation, energy consumption, and trade development can result in carbon emissions. This study aims to examine the effects of GDP per capita, GDP^2, total natural resource rents, renewable energy consumption, and trade openness on CO_2 emissions in selected ASEAN economies from 1995 to 2023. The study is based on the Environmental Kuznets Curve framework, where GDP per capita and GDP^2 are used to test the non-linear relationship between economic growth and CO_2 emissions. Annual panel data are used for Cambodia, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. The research uses the cross-sectional dependence test, Pesaran CIPS second-generation panel unit root test, and CS-ARDL estimation method. The findings confirm that there is cross-sectional dependence on most of the variables and that the variables are mixed in their order of integration. The CS-ARDL results support the Environmental Kuznets Curve hypothesis, as GDP per capita has a positive effect on CO_2 emissions, while GDP^2 has a negative effect. The findings also show that total natural resource rents increase CO_2 emissions, indicating that resource dependence creates environmental pressure in ASEAN economies. In contrast, renewable energy consumption reduces CO_2 emissions in both the short run and long run. Trade openness has an insignificant effect on CO_2 emissions. The research suggests that the economies of ASEAN need to enhance natural resource management, increase investment in renewable energy, and harmonize economic growth and trade policies with low-carbon development policies.

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1. Introduction

Environmental degradation and climate change have emerged as the main policy issues of emerging and developing economies, especially in areas where economic growth, trade, and integration, natural resource exploitation and energy consumption are all on the rise. The past three decades have witnessed a fast structural change in the ASEAN economies,

which have been facilitated by industrialization, export-led growth, urbanization, and increased energy consumption. Nevertheless, this has been accompanied by an increased worry about carbon emissions and environmental sustainability. In this regard, the interaction between economic growth and environmental degradation has been largely studied in terms of Environmental Kuznets Curve (EKC) hypothesis, which states that environmental pressure grows with income, but it can decline following some degree of development because of the cleaner technologies, improved institutions, and more robust environmental policies. The earlier literature has utilized the EKC framework to address emerging economies by introducing energy use, renewable energy, trade openness, and reliance on natural resources as critical factors in carbon emissions (Amin & Song, 2023; Baloch et al., 2022; Danish et al., 2019; Zafar et al., 2019). Likewise, the previous studies have also evidenced population growth, economic growth, energy use, urbanization, and per capita energy use as the key factors in driving the CO_2 emissions, especially in the context of ASEAN and developing countries (Ahmad et al., 2020; Ahmad et al., 2022; Ahmad, Kiran, et al., 2023; Ahmad, Nawaz, et al., 2023; Zafar et al., 2019).

The aspect of natural resource rents is critical in the energy-environment debate as it can either contribute towards economic development or worsen the environmental degradation, depending on how the resource revenues are spent. According to the resource school of thought, the dependence on the resources can enhance emissions due to extractive activities, fossil fuel dependence, ineffective governance, and the slow pace of structural change. Nonetheless, other studies have found that there are mixed results with the rents of natural resources not having significant effects on emissions in countries and regions and even mitigating effects. Indicatively, Danish et al. (2019) studied the BRICS countries and discovered that the impacts of natural resources on CO_2 emissions were heterogeneous, and Voumik et al. (2023) that employed a CS-ARDL model to study South Asian countries revealed that economic growth, urbanization, and industrialization elevated emissions, and natural resource rents played a limiting role in this region. Such ambivalent results suggest that the environmental effects of natural resource rents are region-specific and need to be researched further at the regional level, particularly in ASEAN economies due to the significant variations in the structure of resources across countries, such as Indonesia, Malaysia, Vietnam, Thailand, Singapore, Cambodia, and the Philippines.

Another important variable that can be used to explain carbon emissions is the use of renewable energy. The shift towards renewable energy sources is the most common perspective on the way to decrease the level of emissions and attain sustainable development. Empirical research tends to indicate that the use of renewable energy sources lowers CO_2 emissions, whereas the use of non-renewable energy sources raises the pressure on the environment. In an EKC-based study about emerging economies, Zafar et al. (2019) have found that the usage of renewable energy sources has a negative impact on the amount of CO_2 emitted, but the use of non-renewable energy sources has a positive impact on the emission levels. On the same note, Amin and Song (2023) explored South and East Asian nations and highlighted how renewable energy, trade, urbanization, and economic growth can help to reach carbon neutrality. These conclusions can be applied to ASEAN since the region is confronted with a twofold problem: how to continue the growth of the economy and at the same time increase the rate of renewable energy transition to slow down the carbon intensity.

The nexus of emissions and growth is also a complex relationship involving trade openness. On the one hand, trade can accelerate emissions due to the scale effects, industry output, and exports that require a lot of energy. Conversely, trade can enhance the quality of the environment through technology transfer, cleaner production process, and availability of energy efficient products. Zafar et al. (2019) added the trade openness to the EKC framework and emphasized its importance in elucidating the environmental results in emerging economies. Trade openness is especially critical to ASEAN economies as the region is highly connected to the global production networks. So, the environmental impacts of trade can be conditioned by the trade growth along with cleaner technologies, the use of renewable energy and the implementation of more stringent environmental regulation.

The importance of the current research is that it covers ASEAN economies in the period of 1995-2023 when the economies experienced high growth rates, trade integration, resource exploitation, and growing attention to environmental policies. This research is significant in three ways. First, the countries of ASEAN are characterized by different economic and resource frameworks, including highly industrialized and service-based economies, resource-dependent and manufacturing-based economies. Second, the paper connects the natural resource rents, transition to renewable energy, and trade openness to an EKC framework, enabling a wider knowledge of the relationship between income growth and structural factors and carbon emissions. Third, through the application of sophisticated panel econometric tests such as cross-sectional dependence test, Pesaran panel unit root test and CS-ARDL estimation, the research considers the interdependence of regions and heterogeneous long-term dynamics among ASEAN economies. The reference base used in this research consists of various pertinent studies on natural resource rents, renewable energy, trade openness, EKC and carbon emission, which offer good theoretical and empirical basis to the proposed model.

Despite the growing literature, the existing body of research critically lacks a robust identification and articulation of a novel research gap in the ASEAN context. Numerous studies analyze the correlation of natural resources, renewable energy, economic growth, and emission in BRICS, MENA, G7, South Asia, Sub-Saharan Africa, and other emerging economies, whereas fewer studies present the evidence of ASEAN-specific using the combined framework of natural resource rents, renewable energy transition, trade openness, and EKC. In addition, some of the past studies rely on traditional panel estimators, which might not consider cross-sectional dependence, which is quite pertinent to ASEAN since they share trade networks, investment flows, common energy-market shocks, and climate-policy spillovers. Thus, this research fills this gap by evaluating the hypothesis of the EKC in the chosen ASEAN countries considering the natural resource rents, renewable energy usage, and trade openness based on a CS-ARDL model.

The rest of the paper is organized as follows. Section 2 examines the literature on the topic and makes up the theoretical framework of the research. Section 3 describes the data, variables, model specification and econometric methodology. The empirical results and discussion are given in section 4. Section 5 summarizes the research and gives policy implications of the research to ASEAN economies.

2. Literature Review

Economic growth and environmental degradation have been one of the most discussed questions of energy and environmental economics. The Environmental Kuznets Curve (EKC) is an excellent theory that can be used to analyze the idea of environmental pressure growing in the initial phases of economic growth and decreasing when the economies reach a greater level of income. Under this system, the GDP per capita is likely to raise CO_2 emissions first due to the growth in industrialization, urbanization, expansion in production as well as energy demand which puts a strain on the environment. Nevertheless, the GDP per capita squared term should decrease emissions as more income will allow more environmentally friendly technologies, more environmental controls, the implementation of renewable energy, and structural change to less carbon-intensive industries. Several studies have tested EKC hypothesis with the inclusion of income, renewable and non-renewable energy consumption, openness to trade, natural resources, financial development and institutional quality as contributing factors to emissions. Zafar et al. (2019) explored the issue of renewable energy, non-renewable energy consumption, trade openness and CO_2 emission in the EKC framework of emerging economies, and Danish et al. (2019)studied the impact of natural resources, renewable energy, and the economic development in BRICS countries. Such studies point to the fact that the income-emissions nexus is also very context-specific and might vary depending on the energy structure, reliance on resources, and quality of policies.

Natural resource rents constitute a significant part of the environmental sustainability discussion since the extraction of resources, and the income of a resource can be a

determinant of economic development and environmental degradation. In theory, the rents of natural resources can exert a positive effect on CO_2 emissions by extractive production, reliance on fossil fuels, land-use stress, industrial growth, and ineffective incentives to diversify the economy. This argument is in line with the resource curse view which posits that the economies that are reliant on resources can experience inefficiency in the environment if the revenues of the resources are not converted to cleaner production systems. The research by Akadiri et al. (2023), Arslan et al. (2022), Danish et al. (2019), Huang et al. (2023), and Khan et al. (2023) demonstrates the relevance of natural resource rents to the environment in various groups of countries. Their results tend to indicate that natural resources have the potential to enhance environmental degradation when resource exploitation is linked to energy consumption, which is carbon-demanding and poor environmental management. On the same note, Muhammad and Khan (2021) and Muhammad et al. (2021) point out that the emission in developed, developing, and global samples is a confluence of natural resources, renewable energy, globalization, and economic factors. Thus, natural resource rents cannot be considered as an economic factor of growth only, they must be researched as the possible source of environmental pressure.

But the relationship between the natural resource rents and emissions is not always linear. Natural resource rents are found to boost CO_2 emissions in some studies, and no, mixed and even negative impacts in others. An example is Adanu and Adams (2022) who claim that natural resource rents might not be an appropriate corrective policy instrument to manage carbon emissions in Sub-Saharan Africa. Employing CS-ARDL method to analyze South Asia, Voumik et al. (2023) demonstrate that urbanization and industrialization are significant factors in generating anthropogenic carbon emissions, whereas the role of natural resource rents can depend on the circumstances in the regions. Sibanda et al. (2023) also re-examine the natural resource rents and environmental quality by considering the corruption control and the results reveal that the governance conditions can impact the environmental implications of resource rents. These inconclusive findings suggest that the effects of the emissions of the natural resource rents are conditional on the institutional quality, energy transition, industrial structure, and the management of the resource revenues. The problem is of specific concern in ASEAN countries, as they include resource-exporting economies (Indonesia and Malaysia), manufacturing-oriented economies (Vietnam and Thailand), and service-based economies (Singapore). Thus, ASEAN setting is an interesting environment to test the hypothesis that natural resource rents can either increase or decrease carbon emissions.

Another key aspect of the trend of carbon emissions of developing and emerging economies would be renewable energy consumption. Renewable energy, in theory, will minimize CO_2 emissions by substituting fossil fuels, diversify energy, and encourage a low-carbon development pathway. Adebayo et al. (2022) demonstrate that the use of renewable energy is a major factor in decreasing consumption-based carbon emissions in MINT economies. On the same note, Ali et al. (2023) present evidence on Asian emerging economies that there are varied environmental impacts on renewable and non-renewable energy consumption where renewable energy tends to promote emissions reduction (Shah et al., 2021). Amin and Song (2023) discuss South and East Asian nations and the role of renewable energy, non-renewable energy, trade, economic growth and urbanization in the realization of carbon neutrality. This research proves the thesis that the renewable energy transition is not merely a question of the energy sector, but a key mechanism of environmental policy.

The relationship between renewable energy and the emissions is particularly pertinent to the ASEAN economies since the region is experiencing rising energy demand with population growth, industrialization, urbanization, and growing trade networks. Despite the gains achieved in the adoption of renewable energy, fossil fuels continue to dominate electricity production, transport and production of industrial products, particularly in the ASEAN economies. Previous research by Khan, Han, et al. (2022), Khan et al. (2023), Li, Alharthi, et al. (2022) and Kuo et al. (2022) can be used to support the fact that the renewable energy, natural resources and economic growth are intertwined with the

environmental quality within Asian, Belt and Road, and developing economies. Li, Mehmood, et al. (2022) link renewable energy, natural resources, carbon emissions, and transboundary trade relationships in the Southeast Asian context, thus directly applicable to the ASEAN economies. According to these studies, the use of renewable energy can be used to decrease the amount of carbon emissions, but its efficiency may be based on the rate of energy shift, the proportion of fossil fuels in the energy mix, and the industrial growth through trade.

Another determinant of environmental outcome is trade openness since it influences the scale of production, transfer of technology, export structure and specialization in the industry. Theoretically, trade openness may have a positive or negative impact on CO_2 emissions. The scale effect states that trade growth can bring about more emissions as it brings about more production, transportation and manufacturing that are energy intensive. The technique effect states that trade can lead to lowering of emissions through easier technologies, environmental regulation, and effective production processes. The composition effect argues that, trade has an environmental impact that is determined by whether nations are specialized in a more pollutant or cleaner sector. Alola et al. (2019) look at how trade policy, economic growth, fertility, and energy consumption have a dynamic effect on ecological footprint in Europe, whereas Zafar et al. (2019) introduce the trade openness as the part of the EKC framework to the emerging economies. The research of Ibrahim (2022) also focuses on the energy consumption, resource dependence, and trade openness about carbon neutrality in G20 countries. These works confirm that trade openness should be incorporated in the emissions models since it represents one of the key channels by which globalization impacts the quality of the environment.

In the case of ASEAN countries, the openness to trade is especially significant as regional economies are closely linked to the global value chains. Export-led growth and increased involvement in global production networks have been witnessed in countries like Vietnam, Thailand, Malaysia, Singapore, Indonesia, the Philippines and Cambodia. This integration can augment emissions in case production is based on fossil fuels and energy intensive production. But trade can also enhance environmental quality provided it helps in transfer of technology, green investment and production which is clean. Other studies like Danish (2019), Dingru et al. (2023), Mahmood (2023), Thi et al. (2023), and Wang, Yang, et al. (2023) draw attention to the topicality of trade, renewable energy, natural resources, and carbon emissions in the regional and methodological context. The inconclusive results on the literature indicate that the trade-emissions relationship is not predetermined, but it is dependent on the type of traded products, energy composition of production, and the policy environment.

Economic growth has been at the heart of the debate on emission since development usually involves increased energy consumption, building of infrastructure, industrial production, and transport. Nevertheless, according to the EKC hypothesis, there is a limit to the income that countries can reach to cleaner technologies and more robust environmental policies. The income-emissions relationship has been studied with other variables like renewable energy, natural resources, urbanization as well as financial development. As an illustration, Gyamfi et al. (2022) consider the joint effects of natural resource rents, income level, and energy consumption on the quality of the environment in G7 economies with the help of panel quantile regression. Tauseef Hassan et al. (2020) explore the relationship between natural resources, income and CO_2 emission and sustainable development pathways. The quantile regression presented by Boyce and He (2023) also offers an insight into the drivers of CO_2 emission in a carbon-conscious world. These studies show that income cannot be used to explain the pattern of emissions, but on the contrary, emissions are influenced by the availability of renewable energy, efficient management of the resources and regulation of the environment.

Recent literature also, in its methodological approach, is increasingly giving weight to the significance of advanced panel techniques since countries do not exist in vacuums as far as each other is concerned. Cross-sectional dependence can be because of common energy shocks, trade linkages, technology spillovers, financial integration, diffusion of regional policy

and climate-related shocks. The traditional panel techniques, which do not consider cross-sectional dependence, can give biased or unreliable estimates. Thus, other heterogeneous panel estimators like CS-ARDL, AMG, CCEMG, panel quantile regression, and others have been employed in recent studies. Voumik et al. (2023) apply the CS-ARDL model to research urbanization, industrialization, natural resource rents, and anthropogenic carbon emissions in South Asia. Another study by Khan et al. (2023) examines the natural resources, consumption of renewable energy, economic growth and CO_2 emissions in the BRI countries through the advanced panel techniques. The present study justifies the use of CD testing, Pesaran panel unit root testing and CS-ARDL estimation due to these methodological developments. As the countries in the ASEAN region are economically linked, in terms of trade, investment, energy markets, and regional cooperation, the cross-sectional dependence needs to be controlled.

Although literature has been growing, there are still several gaps. To begin with, much of the research is done on BRICS, G7, MENA, G20, OECD, Sub-Saharan Africa, South Asia and countries with resources, but there is a relative paucity of evidence on ASEAN. Second, there is a general lack of literature that combines natural resource rents, the consumption of renewable energy, trade openness, GDP per capita, and GDP squared in a single EKC model, even though these factors are related to ASEAN. Third, some of the previous research is based on the traditional panel approaches that might not adequately consider cross-sectional dependence and long-run heterogeneity. This is a severe constraint to the economies of ASEAN countries since they are connected by the flows of trade, regional value chains, exposure to energy markets and shared environmental issues. Fourth, the literature at hand has a critical weakness of not identifying and defining a new research gap with respect to whether the rent of natural resources and renewable energy transition redefines the EKC pattern in ASEAN economies. Thus, the current research paper is relevant to the literature as it tests the EKC hypothesis of ASEAN nations during 1995-2023 and considers the natural resource rents, use of renewable energy, and openness to trade using CD testing, Pesaran panel unit root testing, and CS-ARDL estimation. This method will give a better region-specific and methodologically sound evidence on long-run drivers of CO 2 emissions in the ASEAN economies.

3. Data and Methodology

3.1. Development of Theoretical Basis and Model

The present study is based on the Environmental Kuznets Curve (EKC) hypothesis which describes the non-linear relationship between economic growth and environmental degradation. According to the EKC framework, in the initial stages of economic development, the levels of environmental degradation rise since countries are expanding industrial production, energy consumption, infrastructure, urbanization and output related to trade. Nevertheless, at a higher income level, the rate of environmental degradation might decrease, as economies start to use more clean technologies, become more energy efficient, enhance environmental regulation, and turn to service-based and knowledge-based economies. Thus, the EKC hypothesis is usually challenged by adding to the emissions model GDP per capita and the squared GDP per capita. The fact that the coefficient of GDP is positive and that of GDP^2 is negative, shows that there is an inverted U-shaped relationship between economic growth and CO_2 emissions.

In this research, the dependent variable is CO2 emissions, and it is an indicator of environmental degradation in the chosen ASEAN economies. The EKC hypothesis is tested by using GDP per capita and GDP^2. Natural resource rents are incorporated since the extraction of resources and the income based on resources can contribute to the rise of emissions by relying on fossil fuels, extractive operations, and the production of goods based on resource-intensive production. The consumption of renewable energy is also captured since the shift towards renewable energy will minimize carbon emission as the use of fossil-based sources of energy will be eliminated. The openness to trade is incorporated since the economies of ASEAN are well integrated in the international production and trade networks. Trade can cause emissions by expanding production and by transportation activities or can cause a

decrease in emissions by transfer of technology and cleaner production techniques. These are the variables that are frequently employed in recent research on natural resources, renewable energy, economic growth, openness of trade, and environmental quality. Figure 1 presents the framework of the study.

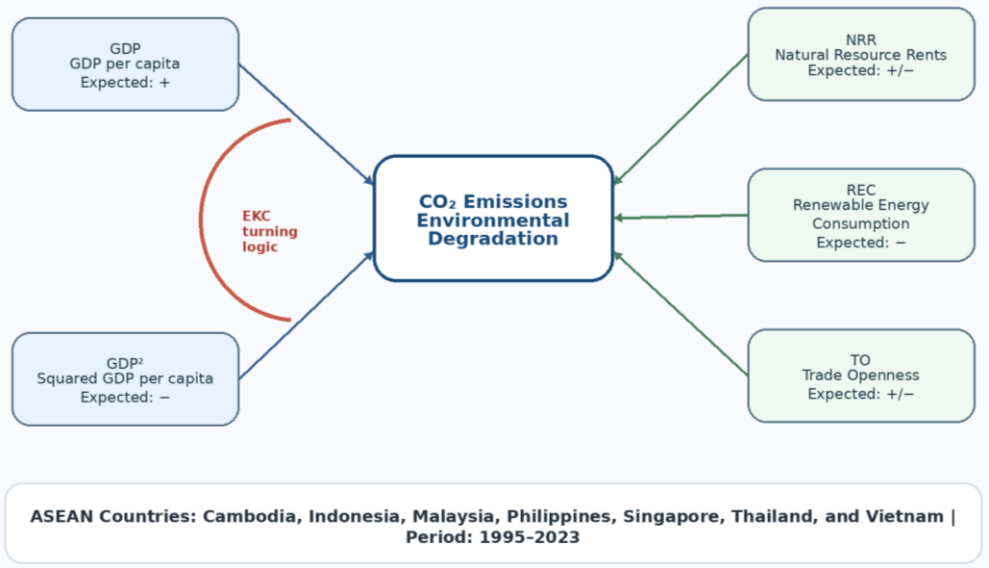

Figure 1: Conceptual Framework of the Study

The general functional form of the model is expressed as:

$$CO2_{it} = f(GDP_{it}, GDP2_{it}, NRR_{it}, REC_{it}, TO_{it}) \quad (1)$$

Where $i$denotes country and $t$denotes time. $CO2$ represents carbon dioxide emissions, GDP represents GDP per capita, $GDP2$ represents squared GDP per capita, NRRrepresents total natural resource rents, RECrepresents renewable energy consumption, and TOrepresents trade openness.

The baseline econometric model is specified as:

$$CO2_{it} = \alpha_0 + \beta_1 GDP_{it} + \beta_2 GDP2_{it} + \beta_3 NRR_{it} + \beta_4 REC_{it} + \beta_5 TO_{it} + \varepsilon_{it} \quad (2)$$

For estimation, CO_2 emissions and GDP per capita are transformed into natural logarithms to reduce scale differences and improve elasticity-based interpretation. Since NRR, REC, and $TO$are measured as percentages, they are retained in their original form. Thus, the final model is written as:

$$CO2_{it} = \alpha_0 + \beta_1 GDP_{it} + \beta_2 GDP2_{it} + \beta_3 NRR_{it} + \beta_4 REC_{it} + \beta_5 TO_{it} + \varepsilon_{it} \quad (3)$$

In the EKC framework, β1 is expected to be positive and β2 is expected to be negative. This implies that the number of emissions rises with income but beyond a certain level of development, the level offsets and the emissions start to decrease. The coefficient of NRR can be positive when natural resource rents augment extractive and carbon-intensive actions. The REC coefficient will be negative since the consumption of renewable energy is supposed to decrease emissions. The coefficient of TO can be either positive or negative due to the possibility of either scale-related emission being increased or cleaner technologies and efficient production to be promoted by the expansion of trade.

3.2. Data, Variables, and Justification

This research is based on the annual panel data of the chosen ASEAN economies between 1995 and 2023. The countries chosen are Cambodia, Indonesia, Malaysia, the

Philippines, Singapore, Thailand and Vietnam. The choice of these countries is since the needed variables are accessible during the study period and that they are representatives of the different degrees of economic development, reliance on the natural resources, adoption of renewable energy, and integration into the ASEAN trading zone. The data is collected from the World Development Indicators (WDI). GDP^2 is calculated by taking the square of GDP per capita. Table 1 presents the description of the variables

Table 1
Variable Description, Measurement, Source, and Justification

Variable	Abbreviation	Measurement	Source	Justification
Carbon emissions	CO_2	Carbon dioxide emissions excluding LULUCF, Mt CO_2	WDI	Used as the dependent variable to measure environmental degradation and carbon pressure in ASEAN economies.
Economic growth	GDP	GDP per capita	WDI	Used to capture income level and test the first stage of the EKC hypothesis.
Squared income	GDP^2	Square of GDP per capita	Calculated	Used to test the non-linear EKC effect. A negative coefficient supports the inverted U-shaped EKC relationship.
Natural resource rents	NRR	Total natural resource rents (% of GDP)	WDI	Captures resource dependence and examines whether resource rents increase or reduce environmental degradation.
Renewable energy consumption	REC	Renewable energy consumption (% of total final energy consumption)	WDI	Represents the renewable energy transition and is expected to reduce CO_2 emissions.
Trade openness	TO	Trade (% of GDP)	WDI	Captures external economic integration and its possible scale, composition, and technology-transfer effects on emissions.

3.3. Econometric Strategy

The empirical analysis consists of three broad steps. To analyze the transmission of shocks in one country of the ASEAN to other countries, the cross-sectional dependence test is used first. This matters since the ASEAN economies are integrated in terms of trade, investment flows, production networks, energy markets and cooperation on regional policies. Second, the xtcips command is used to test the stationarity properties of the variables using the Pesaran CIPS panel unit root test. Third, Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model is estimated to test long-run and short-run associations between $lnCO_2$, GDP, GDP^2, NRR, REC and TO. The sequence of the tests performed is given Figure 2.

3.4. Cross-sectional Dependence Test

Another critical problem of the panel data analysis is cross-sectional dependence, which is particularly significant when the countries are geographically and economically interdependent. The cross-sectional dependence that may occur in this study is between the countries of ASEAN due to the commonality of trade shocks, energy-price shocks, climate disturbances, investment flows, and regionalized production. Without consideration of cross-sectional dependence, the results of panel unit root and long-run estimation can be biased and unreliable. Therefore, this study first applies to the Pesaran CD test.

The Pesaran CD test is written as:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \quad (4)$$

Where $N$is the number of countries, T is the time period, and $\hat{\rho}_{ij}$is the pairwise correlation coefficient of residuals between countries $i$and j.
The hypotheses of the CD test are:

$$H_0: \rho_{ij} = 0 \quad (5)$$
$$H_1: \rho_{ij} \neq 0 \quad (6)$$

The null hypothesis indicates no cross-sectional dependence, while the alternative hypothesis indicates the presence of cross-sectional dependence. Rejection of the null hypothesis confirms that ASEAN economies are interdependent, and that second-generation unit root and estimation methods are more appropriate.

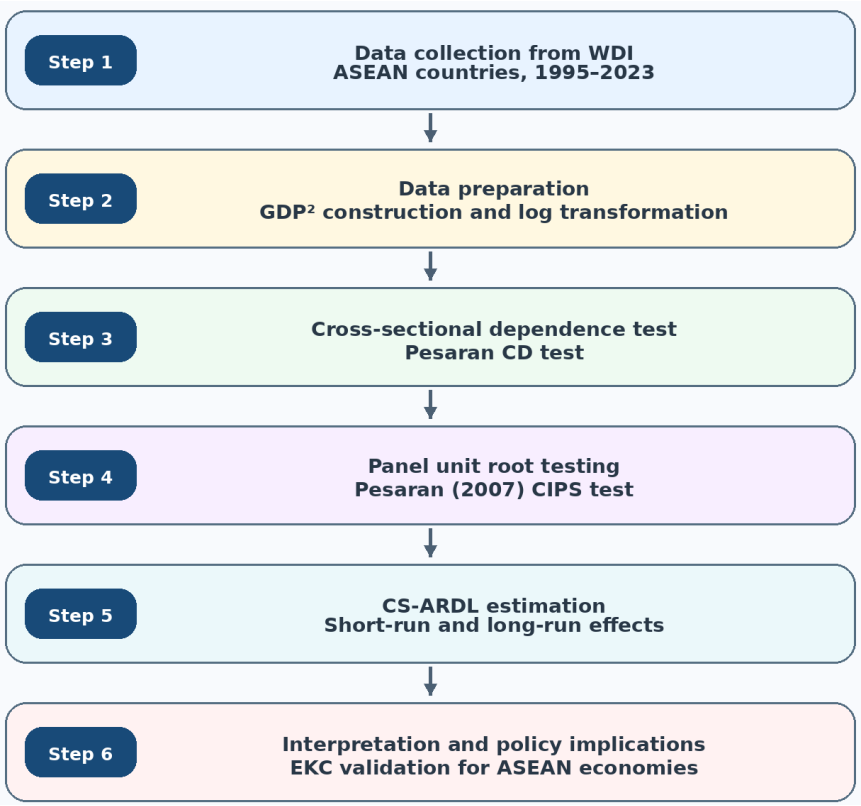

Figure 2: Econometric Flow of the Study

3.5. Pesaran CIPS Second-generation Panel Unit Root Test

After testing cross-sectional dependence, this study examines the stationarity properties of the variables. Unit root testing is necessary because the use of non-stationary variables may produce spurious regression results. Since ASEAN economies are likely to be affected by common regional and global shocks, first-generation panel unit root tests may be inappropriate because they assume cross-sectional independence. Therefore, this study applies the Cross-sectionally Augmented IPS (CIPS) second-generation panel unit root test to verify the stationarity of the variables (Pesaran, 2007).

The CIPS test is based on the Cross-sectionally Augmented Dickey-Fuller (CADF) regression, which extends the standard ADF regression by including cross-sectional averages of the level and first difference of the variable. This augmentation allows the test to account for unobserved common factors and cross-sectional dependence among panel units. The basic CADF equation is written as:

$$\Delta Y_{it} = \alpha_i + \rho_i Y_{i,t-1} + \delta_i \bar{Y}_{t-1} + \theta_i \Delta \bar{Y}_t + \sum_{j=1}^{p} \gamma_{ij} \Delta Y_{i,t-j} + \varepsilon_{it} \quad (7)$$

Where Y_{it}represents the variable being tested, $\Delta$is the first-difference operator, $Y_{i,t-1}$is the lagged level of the variable, $\bar{Y}_{t-1}$is the cross-sectional average of the lagged level, $\Delta\bar{Y}_t$is the cross-sectional average of the first difference, $p$represents the lag length, and $\varepsilon_{it}$is the error term.

The null and alternative hypotheses of the CIPS test are:

$$H_0: \rho_i = 0 \quad (8)$$
$$H_1: \rho_i < 0 \quad (9)$$

The null hypothesis indicates that the variable contains a unit root, while the alternative hypothesis indicates that the variable is stationary. The CIPS statistics are calculated by taking the average of individual CADF statistics across cross-sectional units:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CAD\ F_i \quad (10)$$

Where $N$is the number of countries and $CADF_i$ represents the individual CADF statistic for each country. In this study, the CIPS test is applied to $lnCO2$, $lnGDP$, $lnGDP2$, NRR, REC, and TO. If a variable is stationary at level, it is considered integrated of order zero, I(0). If it becomes stationary after first differencing, it is considered integrated of order one, I(1). The CS-ARDL approach is suitable when variables are integrated at I(0), I(1), or a mixture of both, but it is not appropriate if any variable is integrated at I(2). Therefore, the CIPS unit root test provides the required pre-estimation evidence for applying the CS-ARDL model.

3.6. CS-ARDL Estimation Technique

This study uses the Cross-Sectionally Augmented Autoregressive Distributed Lag model to estimate the long-run and short-run effects of GDP, GDP², natural resource rents, renewable energy consumption, and trade openness on CO_2 emissions. The CS-ARDL approach is appropriate for this study for three reasons. First, it can be used when the variables are integrated at I(0), I(1), or a mixture of both. Second, it accounts for cross-sectional dependence by including cross-sectional averages of the dependent and independent variables. Third, it allows for slope heterogeneity, which is important because ASEAN countries differ in economic structure, resource dependence, energy transition, and trade orientation.

The basic panel ARDL model is expressed as:

$$Y_{it} = \alpha_i + \sum_{j=1}^{p} \lambda_{ij}\, Y_{i,t-j} + \sum_{j=0}^{q} \beta_{ij}\, X_{i,t-j} + \varepsilon_{it} \quad (11)$$

Where $Y_{it}$is the dependent variable, $X_{it}$is a vector of explanatory variables, $p$and $q$represent lag orders, and $\varepsilon_{it}$is the error term. To address cross-sectional dependence, the ARDL model is augmented with cross-sectional averages. The general CS-ARDL model is written as:

$$Y_{it} = \alpha_i + \sum_{j=1}^{p} \lambda_{ij}\, Y_{i,t-j} + \sum_{j=0}^{q} \beta_{ij}\, X_{i,t-j} + \sum_{j=0}^{s} \phi_{ij}\, \bar{Z}_{t-j} + \varepsilon_{it} \quad (12)$$

Where $\bar{Z}_{t-j}$represents the cross-sectional averages of the dependent and independent variables. Using the variables of this study, the CS-ARDL model is specified as:

$$CO2_{it} = \alpha_i + \sum_{j=1}^{p} \lambda_{ij}\, CO2_{i,t-j} + \sum_{j=0}^{q} \beta_{1ij}\, GDP_{i,t-j} + \sum_{j=0}^{q} \beta_{2ij}\, GDP2_{i,t-j} + \sum_{j=0}^{q} \beta_{3ij}\, NRR_{i,t-j} + \sum_{j=0}^{q} \beta_{4ij}\, REC_{i,t-j} + \sum_{j=0}^{q} \beta_{5ij}\, TO_{i,t-j} + \sum_{j=0}^{s} \phi_{ij}\, \bar{Z}_{t-j} + \varepsilon_{it} \quad (13)$$

Where:

$$\bar{Z}_{t-j} = (\bar{CO2}_{t-j}, \bar{GDP}_{t-j}, \bar{GDP2}_{t-j}, \bar{NRR}_{t-j}, \bar{REC}_{t-j}, \bar{TO}_{t-j}) \quad (14)$$

The long-run coefficient can be obtained from the estimated dynamic parameters such as:

$$\theta_i = \frac{\sum_{j=0}^{q} \beta_{ij}}{1-\sum_{j=1}^{p} \lambda_{ij}} \tag{15}$$

The error-correction representation of the CS-ARDL model is written as:

$$\Delta CO2_{it} = \alpha_i + \psi_i(CO2_{i,t-1} - \theta_{1i}GDP_{i,t-1} - \theta_{2i}GDP2_{i,t-1} - \theta_{3i}NRR_{i,t-1} - \theta_{4i}REC_{i,t-1} - \theta_{5i}TO_{i,t-1}) + \sum_{j=1}^{p-1} \lambda_{ij}\, \Delta CO2_{i,t-j} + \sum_{j=0}^{q-1} \beta_{1ij}\, \Delta GDP_{i,t-j} + \sum_{j=0}^{q-1} \beta_{2ij}\, \Delta GDP2_{i,t-j} + \sum_{j=0}^{q-1} \beta_{3ij}\, \Delta NRR_{i,t-j} + \sum_{j=0}^{q-1} \beta_{4ij}\, \Delta REC_{i,t-j} + \sum_{j=0}^{q-1} \beta_{5ij}\, \Delta TO_{i,t-j} + \sum_{j=0}^{s} \phi_{ij}\, \Delta \bar{Z}_{t-j} + \varepsilon_{it} \tag{16}$$

Where $\psi_i$represents the error-correction coefficient. It is expected to be negative and statistically significant. A negative and significant error-correction term confirms that deviations from the long-run equilibrium are corrected over time. For example, if $\psi_i = -0.40$, it means that approximately 40% of the disequilibrium is corrected within one year.

Overall, this methodology is suitable because the selected ASEAN countries are likely to be affected by common regional and global shocks. The Pesaran CD test, the xtcips unit root test and the CS-ARDL model are used to make sure that the analysis takes into consideration the cross-sectional dependence of the variables of interest, mixed integration order, short-run dynamics and long-run equilibrium relationship between the variables of interest.

4. Results and Discussion

This section gives the empirical findings of the study. It starts with summary statistics and correlation analysis, cross-sectional dependence and panel unit root testing. Once it is established that the data is suitable in estimating second-generation panels, the short-run and long-run CS-ARDL results are addressed. The discussion primarily aims at the question of whether GDP and GDP^2 can substantiate the hypothesis of the EKC and the impact of NRR, REC, and Trade on CO_2 emissions within the selected ASEAN economies.

Table 2
Summary Statistics

Variable	Obs.	Mean	STDEV	Min	Max
CO2	203	170.1939	153.3953	1.5014	772.5618
GDPG	203	5.079809	3.657282	-13.1267	14.51975
NRR	203	4.119573	3.89123	0.000169	13.91969
REC	203	29.02204	23.0466	0.3	82.5
EU	203	1645.732	1684.551	258.9473	7371.028
Trade	203	145.0102	96.08213	32.97218	437.3267

Table 2 shows the summary statistics of the study variables of 203 observations of the selected ASEAN economies between 1995 and 2023. The average of the CO_2 emission is 170.1939 and the standard deviation is 153.3953 meaning that there is high variation in the amount of carbon emission between different countries and across time. The lowest and highest CO_2 emissions of 1.5014 and 772.5618 respectively, also represents the variation in the size of the economies of the ASEAN countries, the structure of the industry and the pattern of energy consumption. The average value of GDPG is found to be 5.0798, which demonstrates that the economies in question have had a positive average growth, but the minimum value of -13.1267 and maximum value of 14.5198 show that the growth was very volatile throughout the period of study. The mean value of natural resource rents is 4.1196, indicating the difference between resource dependence among the countries in ASEAN. The mean value of renewable energy consumption is 29.0220, with a large range of 0.3 to 82.5, implying that there are a lot of variations in the use of renewable energy. There is also a significant difference in energy consumption as indicated by the high standard deviation of 1684.551. Trade openness has an average value of 145.0102 which proves that economies

within the ASEAN are very much integrated in international trade. Overall, the descriptive statistics indicate that there is a significant heterogeneity of the chosen ASEAN economies in the context of emissions, growth, and natural resources as well as the use of renewable energy and energy consumption as well as trade openness which justify the application of panel-data methods to the empirical analysis.

Table 3
Correlation Matrix

Variable	CO2	GDPG	NRR	REC	EU	Trade
CO2	1					
GDPG	-0.1885	1				
NRR	0.2389	0.0895	1			
REC	-0.2293	0.2539	0.061	1		
EU	-0.1697	-0.1045	-0.2505	-0.7471	1	
Trade	-0.4083	0.0262	-0.2439	-0.5714	0.8942	1

Table 3 shows the correlation between the variables of the study. The findings indicate that natural resource rents are positively correlated with CO_2 emissions which imply that resource extraction and activities that are dependent on the resources may lead to environmental degradation in the ASEAN economies. Conversely, CO_2 emission has a negative relationship with economic growth, renewable energy use, energy consumption, and trade openness. The negative correlation between the consumption of renewable energy and the emission of CO_2 lends credence to the anticipation that the transition to renewable energy can be used to alleviate pressure on the environment. The correlation table also shows that there is a strong positive relationship between energy use and openness to trade, which means that trade-oriented economies can be characterized by more energy needs. Furthermore, the consumption of renewable energy is found to have a negative correlation with energy use and openness to trade, indicating that not all the economies that are highly trade-oriented and energy-intensive are fully geared towards the renewable energy transition. Correlation analysis however, only gives initial association and does not give causal or long-run relationships. Hence, additional econometric analysis i.e. cross-sectional dependence testing, panel unit root testing, and CS-ARDL estimation is needed.

Table 4
Cross Sectional Dependency Test

Variable	CD-test	p-value	corr	abs(corr)
CO2	22.05	0	0.893	0.893
GDPG	14.06	0	0.57	0.57
NRR	7.29	0	0.295	0.381
REC	-0.12	0.902	-0.005	0.578
EU	15.1	0	0.612	0.612
Trade	4.36	0	0.177	0.412

Table 4 reports the results of the cross-sectional dependence test. The findings show that CO_2 emissions, economic growth, natural resource rents, energy use, and trade openness is statistically significant, indicating the presence of cross-sectional dependence among the selected ASEAN economies. This means that shocks in one country may affect other countries because ASEAN economies are closely connected through trade, investment, energy markets, production networks, and regional economic cooperation. However, renewable energy consumption does not show significant cross-sectional dependence, suggesting that renewable energy adoption may be more country-specific and influenced by domestic energy policies, resource endowments, infrastructure capacity, and national energy-transition priorities. Overall, the presence of cross-sectional dependence in most variables confirms that first-generation panel methods may be inappropriate, and therefore the use of second-generation techniques such as Pesaran's CIPS unit root test and CS-ARDL estimation is justified.

Table 5
Unit Root Test

	Level		First Difference	
Variable	**Cal**	**Tab**	**Cal**	**Tab**
CO2	-1.516	-2.25	-4.665	-2.22
GDPG	-4.203	-2.25		
NRR	-2.533	-2.25		
REC	-2.068	-2.25	-5.051	-2.22
EU	-1.146	-2.25	-4.624	-2.22
Trade	-1.35	-2.25	-4.829	-2.22

Table 5 presents the results of the Pesaran (2007) CIPS second-generation panel unit root test, which is used to verify the stationarity of the variables under cross-sectional dependence. The results show that the variables have mixed orders of integration. Economic growth and natural resource rents are stationary at level, while CO_2 emissions, renewable energy consumption, energy use, and trade openness become stationary after first differencing. This indicates that some variables are integrated of order zero, I(0), while others are integrated of order one, I(1). Importantly, none of the variables is integrated of order two, I(2), which confirms the suitability of the CS-ARDL approach for empirical analysis. Therefore, the unit root results provide strong pre-estimation support for applying the CS-ARDL model to examine the short-run and long-run relationships among CO_2 emissions, economic growth, natural resource rents, renewable energy consumption, energy use, and trade openness in ASEAN economies.

Table 6
CS-ARDL Short Run Results

Variables	**Coef.**	**STDEV**	**z-stats**	**Prob.**
c	2.119	0.772	2.750	0.006
D.CO2	-0.234	0.071	-3.280	0.001
GDPGSQ	0.029	0.016	1.880	0.061
GDPSQ	-0.003	0.001	-1.900	0.057
NRR	0.059	0.024	2.480	0.013
REC	-0.280	0.099	-2.840	0.005
Trade	0.068	0.097	0.700	0.487
ECM	-1.234	0.071	-17.280	0.000

In Table 6, the short-run CS-ARDL results of the chosen ASEAN economies are provided. The findings indicate that the lagged change in CO_2 emissions is negative and statistically significant, meaning that there is a short-run adjustment of carbon emissions. The effect of the GDP-related variable is positive with a weak significance, and the effect of the squared GDP term is negative with a weak significance. This helps to identify the short-run applicability of the EKC hypothesis, that economic growth initially boosts emissions, but beyond a threshold level of economic growth, additional growth can also lead to a decrease in emissions due to the adoption of cleaner technologies, greater efficiency, and better environmental controls. The positive and significant impact of the natural resource rents on CO_2 emissions suggests that resource-dependent activities have negative impacts on the environment in the short run. This observation implies that carbon pressure in the ASEAN economies can be augmented by the extraction of natural resources and production based on resources.

The use of renewable energy influences CO2 emission in a negative and statistically significant manner, which proves that the transition to renewable energy can have a significant impact on the decrease of environmental degradation even in the short term. This finding underscores the need to increase renewable energy sources and to decrease reliance on fossil fuels in ASEAN economies. Openness to trade has a positive but statistically nonsignificant impact, which indicates that trade expansion is not a major factor in carbon emissions in the short run in the selected countries. This can be since scale effect of trade is partially neutralized by transfer of technology, efficiency gains or variation of structure of trade among countries. The error-correction term is negative and very significant, which proves the existence of a long-run equilibrium relationship between the variables. It also

shows that the deviations in short-run equilibrium are corrected in long-run, and this supports the stability of the CS-ARDL model.

Table 7
CS-ARDL Long Run Results

Variables	Coef.	STDEV	z-stats	Prob.
c	1.733	0.697	2.490	0.013
GDPG	0.026	0.014	1.910	0.057
GDPGSQ	-0.002	0.001	-1.790	0.074
NRR	0.050	0.021	2.390	0.017
REC	-0.233	0.084	-2.770	0.006
Trade	0.070	0.084	0.830	0.407

4.1. CS-ARDL Long-Run Results

Table 7 presents the long-run CS-ARDL results. The results indicate that GDP positively and significantly impacts CO 2 emissions whereas GDP 2 has a negative and statistically significant impact. This supports the hypothesis of EKC in the chosen ASEAN economies as it suggests that economic growth, in the beginning, leads to the degradation of the environment, but it reaches a more advanced level of development, further growth will help in reducing emissions. Theoretically, this finding upholds the EKC argument that growth in the early stages is typically associated with industrialization, energy demand, infrastructure development, and production activities, later-stage development may encourage cleaner technologies, environmental consciousness, the adoption of renewable energy, and a firmer policy framework. The results are aligned with (Zafar et al., 2019), who studied renewable energy, non-renewable energy, trade openness, and CO2 emissions in the context of the EKC and (Danish et al., 2019), who discovered that in BRICS economies, economic development and energy-related factors are important determinants of emissions. The role of growth, renewable energy, trade, and urbanization in realizing the carbon neutrality of South and East Asian countries is also reported by (Amin & Song, 2023), who also highlighted similar evidence (Hanif et al., 2022) for ASEAN.

Natural resource rents have a positive and statistically significant long-run effect on CO_2 emissions. This means that ASEAN economies rely on resources and lead to more environmental degradation. This outcome is theoretically compatible with the resource curse and the resource-dependence argument that implies that the rents of natural resources can encourage extractive actions, fossil-fuel burn, mining, land-use stress and energy-intensive production. Unless the resources revenues are channeled to clean technology and environmental management, they can increase carbon emission. Previous studies have too found that natural resources and resources rents have the potential to enhance environmental degradation in various regional and country settings (Akadiri et al., 2023; Arslan et al., 2022; Danish et al., 2019; Jiang et al., 2022; Khan et al., 2023). Nevertheless, the literature demonstrates some mixed evidence as there are some studies that indicate that the environmental impact of natural resources is determined by the quality of governance, energy transition, and the direction of the policy. Thus, in the case of ASEAN economies, the positive externality of NRR implies that the rents of resources should be converted into green investment, development of renewable energy and low-carbon infrastructure.

The consumption of renewable energy negatively and statistically significantly influences CO2 emissions in the long run. This observation supports the fact that transition to renewable energy aids in curbing environmental degradation of the economies in ASEAN. In theory, renewable energy cuts down on the emissions through the substitution of fossil fuels, energy mix diversification, enhances energy sustainability, and helps in cleaner production systems. This finding aligns with the clean energy transition perspective and proves the thesis that renewable energy is a key policy tool towards the low-carbon development or to reduce the environmental pressure that is associated with carbon (Ahmad et al., 2020; Ahmad et al., 2022; Ahmad, Kiran, et al., 2023; Ahmad, Nawaz, et al., 2023). In addition, a number of other studies (Adebayo et al., 2022; Ali et al., 2023; Amin & Song, 2023; Khan, Zakari, et al., 2022; Li, Alharthi, et al., 2022; Zafar et al., 2019) empirically

support this finding since they found that renewable energy use contributes to carbon emissions reduction and environmental sustainability. To the economies of ASEAN, this finding means that a higher ratio of renewable energy to total final energy consumption can be at the core of lowering carbon emissions in the long run.

Openness to trade positively influences CO2 emissions in the long run but is statistically insignificant. This indicates that the openness to trade does not have a standalone effect on long run changes in carbon emission in the sampled ASEAN economies. Theoretically, the impact of trade on emissions is unclear. The scale-effect argument indicates that trade growth can lead to an increase in emissions due to increased production, transportation, and energy consumption. Conversely, the technique-effect argument is the argument that trade can decrease emissions through transfer of technology, capital that is energy efficient and production processes that are cleaner. This minor finding may show that these two opposite effects are canceling out in the ASEAN economies. The result can be compared to the mixed evidence found in other studies, (Ibrahim, 2022; Thi et al., 2023; Wang, Niu, et al., 2023; Zafar et al., 2019) that the environmental impact of trade openness is mixed depending on country structure, energy mix, and environmental policy. In general, the long-run findings indicate that the EKC hypothesis is accepted, natural resource rents positively correlate with CO_2 emissions, renewable energy consumption is negatively correlated with CO_2 emissions and trade openness does not have a significant effect in the long-run in the chosen ASEAN economies.

Overall, the empirical findings affirm that economic growth, natural resource rents and the consumption of renewable energy are significant predictors of CO_2 emissions in the sampled ASEAN economies. The positive value of GDP coefficient and negative value of GDP^2 coefficients supports the hypothesis of the Environmental Kuznets Curve that states that the level of emissions initially increases with the growth of the economies but then decreases as economies enter a more advanced level of development. The rents on natural resources contribute to CO_2 emissions both in the short and the long run, indicating that resource dependence continues to be a problem to the ASEAN economies in the context of resource revenues being associated with extractive and carbon-intensive sectors. Conversely, the level of CO_2 emission into the atmosphere by renewable energy use is minimal, which corroborates the fact that a shift towards renewable energy will enhance the sustainability of the environment. The openness of trade is insignificant, which means that trade itself is not a determinant of emission outcomes except when it is accompanied by cleaner technologies, green industrial policies and environmental regulations. Thus, the results indicate that the ASEAN countries should more sustainably regulate the rents of natural resources, increase investment in renewable energy faster and harmonize economic and trade growth with the low-carbon development policies.

5. Conclusion

This paper has analyzed how natural resource rents, renewable energy, economic growth, and trade openness affect CO_2 emissions of the chosen ASEAN economies between 1995 and 2023. The research was formulated in the Environmental Kuznets Curve model and employed second-generation panel methods, such as cross-sectional dependence test, Pesaran CIPS unit root test and CS-ARDL estimation. The results proved that there is cross-sectional dependence between most of the variables which means that there is interdependence between the ASEAN economies in terms of trade, investment, energy markets and regional economic linkages. The unit root findings indicated that there are mixed orders of integration of the variables and that the CS-ARDL approach is appropriate. The long-run findings proved the hypothesis of the EKC since GDP positively influenced CO_2 emissions and GDP^2 had a negative influence. This means that at the beginning of the economic growth emissions increase but as the level of development increases, the additional growth can be used to reduce emissions by using cleaner technologies, more efficient energy use and better environmental control.

5.1. Theoretical and Practical Implications

The research has significant theoretical implications on the literature of energy-environment. First, it expands the EKC framework by including the natural resource rents, the use of renewable energy, and the openness to trade in the ASEAN scenario. Second, it adds to the resource-environment debate by demonstrating that the natural resource rents enhance the CO_2 emissions, which proves the argument that the resource dependence may be environmentally detrimental when it is not sustainable. Third, it reinforces the existing literature on the topic of renewable energy transition as it proves that the use of renewable energy sources lowers CO_2 emissions in both the short term and the long term. These results point to the fact that the EKC process cannot be automatic; instead, the environmental benefits of economic growth are determined by the way countries cope with the process of energy transition, rents on resources, and production structure.

Practical contributions are also provided in the study. The findings suggest to policy makers that economic growth is not enough to alleviate the pressure on the environment by ASEAN economies. The governmental revenues on natural resources must be reallocated towards renewable energy, clean infrastructure, green technologies, and green restoration. There should be more resource governance mechanisms introduced by governments to minimize the carbon intensity of the extraction-based sectors. As renewable energy can greatly decrease emissions, ASEAN countries must increase their investment in renewable energy, enhance grid connectivity, motivate the involvement of the private sector, and decrease fossil fuel reliance. The openness of trade was also found to be unimportant, and this implies that the trade policies ought to be aligned with green industrialization, transfer of clean technologies and environmental standards.

5.2. Limitations and Future Research Directions

There are certain limitations in the study. It concentrates on the chosen ASEAN economies because of the availability of data and model incorporates a small number of variables. Future research can incorporate more countries in the ASEAN region, industry level, quality of institutions, green technology, energy intensity or environmental policy indicators. Future studies can also be done in comparison to South Asia, BRICS or OECD economies to establish regional variations. Further research can also use nonlinear methods or quantile-based approaches or country-specifics to measure the heterogeneous effects at various development levels. Overall, the results indicate that sustainable environmental development in ASEAN needs a balanced approach that entails economic development, sustainable management of resources, growth in renewable energy, and an environmentally friendly trade and industrial policy.

Authors Contribution

Muhammad Azhar Bhatti: conceptualized the research idea, developed the study framework, designed the econometric model, collected and organized the data, conducted the empirical analysis, interpreted the results, and prepared the initial draft of the manuscript.
Tusawar Iftikhar Ahmad: contributed to the refinement of the research methodology, provided academic supervision, reviewed the econometric strategy, improved the theoretical and policy arguments, and critically revised the manuscript for intellectual content.
Amina Alamgir: literature review, data verification, formatting of tables and references, and assisted in manuscript editing and proofreading.

Conflict of Interests/Disclosures

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