The impact of economic growth, inequality, and resource depletion on CO_2 emissions in Indonesia: Evidence from the ARDL model

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Abstract.
This study examines the impact of natural resource depletion, economic growth, and income inequality on CO_2 emissions in Indonesia from 1990 to 2021. Utilizing time series data from the World Bank, the analysis employs the Auto-Regressive Distributed Lag (ARDL) model to simultaneously assess both short- and long-run relationships among the variables, while also testing the validity of the Environmental Kuznets Curve (EKC) hypothesis. The results reveal that natural resource depletion, economic growth, and income inequality all have a positive and statistically significant effect on CO_2 emissions in both the short and long term. Furthermore, the findings provide strong empirical support for the existence of an inverted U-shaped EKC in Indonesia, indicating that emissions initially rise with income but eventually decline beyond a certain income threshold. These results underscore the crucial need for comprehensive policy frameworks that effectively integrate economic development, environmental sustainability, and social equity. In particular, the significant role of resource depletion necessitates prioritizing sustainable resource management strategies—such as forest conservation, responsible mining practices, and improved resource efficiency—to mitigate environmental degradation.

Keywords: *Economic growth, Resource depletion, CO_2 Emissions, Inequality, EKC.*

JEL Classification: D31, O13, Q54, Q56

INTRODUCTION

A central challenge for human civilization is achieving sustainable development by balancing economic growth, social equity, and environmental preservation. In response, the United Nations (UN) launched the Sustainable Development Goals (SDGs) framework in 2015 to guide global and national efforts toward sustainable progress (Abbasi et al., 2021). The SDGs comprise 17 goals, 169 targets, and 232 indicators designed to integrate these three dimensions of development (Mehmood et al., 2023; United Nations, 2015; Zafar et al., 2021). Sustainable development can be realized by maintaining equilibrium among these dimensions (Litasari, 2018). This balance is expected to produce significant economic multiplier effects, reduce CO_2 emissions, and enhance income distribution (Endriana et al., 2016).

CO_2 emissions, primarily resulting from the combustion of fossil fuels and unsustainable economic activities, are a significant contributor to climate change. Economic growth and energy consumption are closely associated with rising CO_2 emissions (Wang et al., 2019). In this context, climate change—particularly the increase in carbon dioxide emissions—has emerged as a critical global concern. While developed nations have adopted ambitious emission reduction targets (e.g., the UK aims to reduce emissions by 31% from 2019 levels to achieve net-zero by 2050), developing countries such as Indonesia face more complex trade-offs due to their reliance on extractive industries and limited access to green technologies (Adedoyin & Zakari, 2020; Evans, 2020; Abbasi et al., 2021).

Over the past few decades, Indonesia has experienced substantial economic growth, but this expansion has accelerated the depletion of natural resources and environmental degradation (Abbasi et al., 2021). Major emission sources include the industrial, transportation, and energy sectors, particularly in developing economies like Indonesia (He et al., 2018). Environmental degradation not only threatens ecosystems but also directly undermines the social and economic well-being of communities. This unsustainable trajectory necessitates a shift toward a development model that preserves natural resources and protects the environment (Ocampo, 2012; UNEP, 2011). As part of this effort, the United Nations has promoted the "green economy" concept, which offers a strategic framework to address both environmental challenges and global economic instability (Ocampo, 2012).

Economic growth, typically measured by Gross Domestic Product (GDP), is strongly linked to CO_2 emissions (Ren et al., 2020). As a developing country heavily dependent on fossil fuel-driven GDP, Indonesia has begun implementing strategic policies aimed at decarbonization and sustainable development. Regulatory instruments—including long-term energy planning, carbon pricing, and international climate commitments—have led to measurable progress in Indonesia's energy transition from the early 2000s through 2024. The Indonesian government plays a central role in this transition. Under Business-As-Usual (BAU) scenarios, Indonesia has pledged to reduce emissions by 26% by 2020, with the potential to reach a 41% reduction contingent on international support (Warr & Yusuf, 2011).

Several policy initiatives have been introduced, including the carbon tax under the Tax Harmonization Law (Law No. 7/2021) and the National Energy General Plan (RUEN), which aims to achieve a 23% share of renewable energy by 2025. The carbon tax, implemented on July 1, 2022, imposes a levy of IDR 30 per kg of CO_2 equivalent on coal-fired power plants, making Indonesia the first Southeast Asian nation to adopt such fiscal measures (Ministry of Finance, 2022). Additionally, Presidential Regulation No. 22 (2017) further supports this initiative. RUEN plays a pivotal role in Indonesia's energy transition, setting ambitious targets of 23% renewable energy by 2025 and 31% by 2050. These efforts align with Indonesia's commitment to the Paris Agreement, which underscores the importance of reducing emissions through a transition to cleaner energy sources (Ministry of Energy and Mineral Resources, 2017).

Although the government has introduced policies such as the carbon tax (Law No. 7/2021) and the National Energy General Plan (RUEN), Indonesia's per capita CO_2 emissions and rate of resource depletion remain relatively high compared to the global average (Ministry of Finance, 2022; World Bank, 2023). This gap between policy commitment and implementation hampers progress toward achieving the Sustainable

Development Goals (SDGs). Indicators related to Indonesia's SDGs are presented in Figure 1. Notably, several indicators—such as CO_2 emissions and the Gini Index—have shown an upward trend.

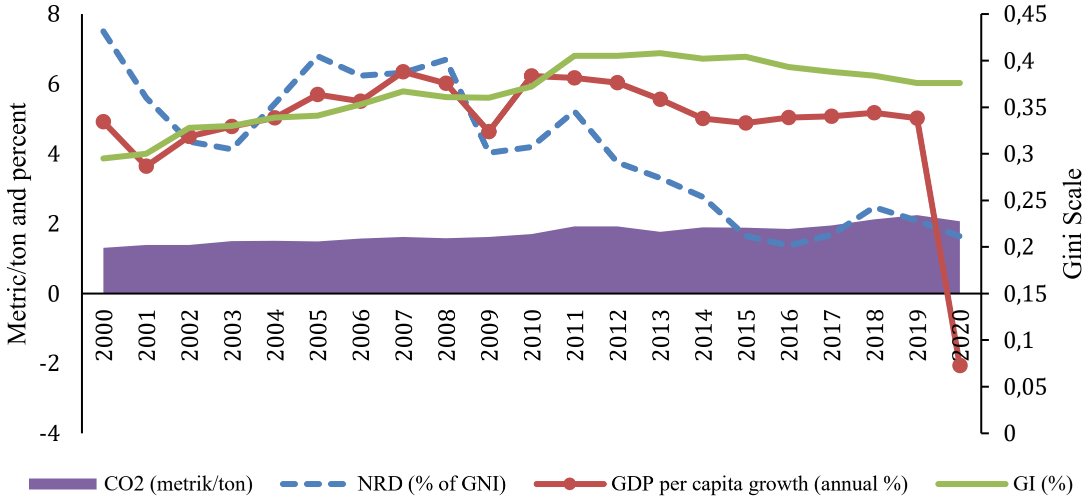

Figure 1. Indonesia's sustainable development goals indicators
Source: World Bank (2023)

While GDP per capita growth experienced a sharp decline in 2020, natural resource depletion has decreased over the past three years. Nevertheless, empirical evidence reveals that CO_2 emissions and income inequality, as measured by the Gini Index, remain persistently high (World Bank, 2023), highlighting a disconnect between policy initiatives and their practical outcomes. Although several studies have explored the relationship between economic growth and CO_2 emissions, few have examined the role of income inequality—particularly in the context of developing countries such as Indonesia. Inequality also contributes to rising emissions: higher-income groups typically consume more energy and contribute disproportionately to CO_2 emissions, whereas lower-income populations often lack access to clean technologies (Ravallion et al., 2000). Therefore, it is essential to incorporate the social dimension into environmental policy frameworks.

In Indonesia, most empirical studies on CO_2 emissions have primarily focused on their relationship with economic growth and energy consumption. For instance, Alfisyahri et al. (2020) and Noor & Saputra (2020) tested the Environmental Kuznets Curve (EKC) hypothesis using GDP and CO_2 emissions data. However, these studies largely relied on static models, such as Ordinary Least Squares (OLS) and panel regressions, which do not account for dynamic interactions or lagged effects. Although a few studies, such as Bashir et al. (2021), employed more sophisticated time-series techniques, they often excluded critical variables, including natural resource depletion and income inequality.

Research investigating the interrelations among economic growth, income distribution, and CO_2 emissions in Indonesia remains limited (Endriana et al., 2016). While Amri (2017) identified a positive correlation between economic growth and emissions, the study did not include inequality as a variable. Indonesia still lacks comprehensive research that dynamically examines CO_2 emissions in relation to both economic and social dimensions (Amri, 2017; Febriyani & Anis, 2022; Hulu & Wahyuni, 2021). Moreover, studies employing updated long-term time-series data and dynamic econometric models, such as the Autoregressive Distributed Lag (ARDL) approach, are scarce. Our review found fewer than five peer-reviewed studies from 2018 to 2023 that tested the EKC hypothesis using time-series methods, and only a small fraction employed the ARDL technique. Many of these studies either focused solely on linear relationships or failed to explore the economic–social–environmental nexus thoroughly.

The primary contribution of this study lies in its integration of income inequality, as measured by the Gini Index, into the analysis of CO_2 emissions. This dimension remains underexplored in Indonesian climate and economic research. The findings suggest that income inequality has a significant and positive effect on emissions, emphasizing the importance of incorporating social justice considerations into climate policy (Ravallion et al., 2000). By addressing the limitations of previous research, this study enhances our understanding of the social factors influencing environmental outcomes.

To fill these gaps, this study incorporates three key variables—natural resource depletion, economic growth, and income inequality—to examine their dynamic effects on CO_2 emissions in Indonesia. Using annual data from 1990 to 2021 and the ARDL method, the study also tests the validity of the EKC hypothesis. It identifies the turning point at which income begins to reduce environmental degradation. The findings contribute to the academic literature and provide evidence-based insights for policymakers to support a just and sustainable low-carbon transition in Indonesia. These results can serve as a reference for the government and stakeholders in formulating more inclusive and effective sustainable development strategies.

METHODS

Data

This study examines the impact of natural resource depletion, economic growth, and income inequality on CO_2 emissions in Indonesia, with a primary focus on the growth rate of CO_2 emissions. The model includes one dependent variable—CO_2 emissions—and three independent variables: natural resource depletion, economic growth, and the Gini Index. The dataset covers the period from 1990 to 2021 and relies entirely on secondary data sourced from the World Bank (WB) database. These data have been processed and validated by relevant institutions.

Table 1 provides detailed information on the variables, their measurement units, and sources. Natural resource depletion is measured as a percentage of Gross National Income (GNI), economic growth is represented by GDP per capita, income inequality is proxied by the Gini Index, and CO_2 emissions are measured in metric tons per capita. All variables are transformed into their natural logarithms to ensure a consistent log-linear model specification. This transformation facilitates coefficient interpretation as elasticities, stabilizes variance, and mitigates issues related to heteroskedasticity and multicollinearity, consistent with the approaches used by Jorgenson et al. (2017) and Baloch et al. (2020).

Table 1. Variable, measurements, and sources

Variables	Measurements	Source
Natural resources depletion (NRD)	% of GNI	WB
Economic growth (EG)	GDP per capita	WB
Gini Index (GI)	Gini Index scale	WB
CO_2 emission (CO_2)	Metric tons per capita	WB

Model specification

This study employs a dynamic Autoregressive Distributed Lag (ARDL) model to investigate the short- and long-term relationships between the selected variables and CO_2 emissions. The ARDL approach is particularly suitable for small-sample time series data. It allows for the integration of variables with mixed levels of stationarity, i.e., I(0) and I(1), without requiring pre-differencing (Pesaran et al., 2001). It also provides efficient parameter estimates and robust long-term equilibrium relationships.

The ARDL method is appropriate for analyzing dynamic systems where lagged effects are relevant, and it enhances the robustness of empirical findings by identifying the long-run economic turning points related to environmental degradation. The estimation process begins with unit root testing, followed by cointegration analysis. Upon confirming the existence of a long-run relationship, the ARDL model estimates both long-run and short-run (error correction) dynamics.

The long-run equation for the ARDL model is specified as follows:

$$lnCO_{2_t} = \alpha_0 + \theta_1 ln\ NRD_t + \theta_2 ln\ GDP_t + \theta_3 (ln\ GDP_t)^2 + \theta_4 ln\ GI_t + \varepsilon t \quad \text{.............. (1)}$$

Where:

$lnCO_{2t}$: Natural log of CO_2 emissions per capita
$lnNRD_t$: Natural log of natural resource depletion (% of GNI)
$lnGDP_t$: Natural log of GDP per capita
$(lnGDP_t)^2$: Squared term for the Environmental Kuznets Curve (EKC) hypothesis
$lnGI_t$: Natural log of the Gini Index
α_0 : Constant
$\theta_1, \theta_2, \theta_3, \theta_4$: Long-run coefficients
ε_t : Error term

The short-run general equation in the ARDL model is formed as follows:

$$\Delta lnCO_{2t} = \alpha_0 + \sum_{i=1}^{p} \beta_0 \Delta lnCO_{2_{t-n}} + \sum_{j=0}^{q} \beta_1 \Delta lnNRD_{t-n} + \sum_{k=0}^{r} \beta_2 \Delta lnGDP_{t-n} + \sum_{l=0}^{s} \beta_3 \Delta (lnGDP^2)_{t-n} + \sum_{m=0}^{t} \beta_4 \Delta lnGI_{t-n} + \lambda\ ECM_{t-1} + \varepsilon t \quad \text{.............. (2)}$$

Where:

Δ : First-difference operator for short-run dynamics
ECM_{t-1} : Error correction term derived from the long-run equation
λ : Speed of adjustment coefficient toward long-run equilibrium

Alternatively, the general ARDL model form combining both short- and long-run terms is expressed as:

$$\Delta lnCO_{2t} = \alpha_0 + \beta_0 \Delta lnCO_{2_{t-n}} + \beta_1 \Delta lnNRD_{t-n} + \beta_2 \Delta lnGDP_{t-n} + \beta_3 \Delta lnGDP^2_{t-n} + \beta_4 \Delta lnGI_{t-n} + \theta_5 lnCO_{2_{t-1}} + \theta_6 lnNRD_{t-1} + \theta_7 lnGDP_{t-1} + \theta_8 lnGDP^2_{t-1} + \theta_9 lnGI_{t-1} + \varepsilon t \quad \text{.............. (3)}$$

The Environmental Kuznets Curve (EKC) hypothesis posits an inverted U-shaped relationship between economic growth and environmental degradation (Grossman & Krueger, 1995). At lower income levels, environmental degradation tends to increase with economic growth. However, after reaching a certain income threshold—known as the "turning point"—further economic growth is associated with improvements in the environment.

The general EKC model is specified as:

$$lnCO_{2_t} = \alpha + \beta_1 lnGDP_t + \beta_2 lnGDP_t^{\,2} + \varepsilon_t \quad \text{.......... (4)}$$

The EKC hypothesis is supported if $\beta_1 > 0$ and $\beta 2 < 0$, indicating an inverted U-shape.

According to Kuznets' hypothesis, an inverted U-curve will appear because the expected coefficient describing the EKC curve is positive at $lnGDP_t$ and negative on $\ln (GDP_t)^2$. To determine the turning point, you can use the logarithmic quadratic function derived from the equation above. The formula for determining the turning point is as follows.

$$\frac{d \ln CO_2}{d \ln GDP} = \beta_1 + 2.\beta_2 \ln GDP \quad \text{.......... (5)}$$

$$0 = \beta_1 + 2\beta_2 \ln GDP \quad \text{.......... (6)}$$

$$\text{Turning point, } \ln GDP = -\frac{\beta_1}{2\beta_2} \quad \text{.......... (7)}$$

To obtain the GDP value at the turning point, the natural logarithm result must be exponentiated (antilogged).

RESULTS AND DISCUSSION

Descriptive statistics and correlation analysis

Table 2 presents the results of the descriptive statistics and correlation matrix, which provide insights into the distributional properties and interrelationships among the study variables. The descriptive statistics summarize the central tendency, dispersion, and shape of the distributions for CO_2 emissions, natural resource depletion, GDP per capita, and the Gini Index. The Jarque-Bera test is employed to assess the normality of the data. The correlation matrix, in turn, illustrates the strength and direction of the linear associations among the variables under investigation.

Table 2. Descriptive statistics and correlation matrix

Statistics	lnCO₂	lnNRD	lnGDP	lnGI
Mean	0.395	1.398	7.778	3.579
Median	0.432	1.474	7.705	3.586
Maximum	0.808	2.276	8.266	3.708
Minimum	-0.205	0.281	7.302	3.384
Std. Dev.	0.279	0.508	0.299	0.094
Skewness	-0.516	-0.686	0.263	-0.353
Kurtosis	2.368	2.771	1.762	2.104
Jarque-Bera	1.954	2.583	2.412	1.464
Probability	0.376	0.274	0.299	0.480
Correlation				
lnCO₂	1.000	-	-	-
lnNRD	-0.677	1.000	-	-
lnGDP	0.926	-0.822	1.000	-
lnGI	0.731	-0.667	0.838	1.000

The descriptive statistics reveal that GDP per capita (lnGDP) has the highest mean value at 7.778, indicating that it is relatively greater in magnitude compared to the other variables. CO_2 emissions, natural resource depletion, and the Gini Index have mean values of 0.395, 1.398, and 3.579, respectively. The standard deviations across all variables are relatively modest, suggesting limited variability around the mean. The skewness values indicate a slight asymmetry in the data distributions, with $lnCO_2$ and lnNRD showing negative skewness, while lnGDP and lnGI exhibit slight positive and negative skewness, respectively. All kurtosis values fall below the threshold of 3, indicating platykurtic distributions, which are flatter than the normal distribution.

The results of the Jarque-Bera test further support the assumption of normality. For instance, the Jarque-Bera statistic for CO_2 emissions is 1.954, with a corresponding p-value of 0.376. Since this value exceeds the 0.05 significance level, the null hypothesis of normal distribution cannot be rejected. Similar conclusions apply to the other variables, as their p-values also exceed 0.05, confirming that the data meet the normality assumption and are suitable for further parametric analysis.

The correlation matrix indicates several significant relationships among the variables. There is a strong and positive correlation between CO_2 emissions and GDP per capita, with a correlation coefficient of 0.926, suggesting that higher levels of income are associated with increased emissions. A similarly strong positive correlation exists between CO_2 emissions and the Gini Index ($r = 0.731$), implying that income inequality may contribute to greater environmental degradation. In contrast, the relationship between natural resource depletion and CO_2 emissions is strongly negative, with a coefficient of -0.677, suggesting an inverse association that may reflect changes in energy use or production structures.

GDP per capita also exhibits a strong negative correlation with natural resource depletion, at -0.822, which suggests that economic development is associated with a reduced reliance on resource-intensive activities. The Gini Index also exhibits a negative relationship with natural resource depletion, at -0.667, suggesting complex interactions between inequality and environmental resource use. Lastly, GDP per capita and the Gini Index are strongly positively correlated, with a coefficient of 0.838, indicating that economic growth has been accompanied by rising income inequality.

Stationarity and cointegration tests

Unit root testing using the Augmented Dickey-Fuller (ADF) method indicates that all variables are non-stationary at the level but become stationary after first differencing, i.e., they are integrated of order one, I(1). Unit root testing is applied to determine whether variables in the model—namely, CO_2 emissions, natural resource depletion, economic growth, and income inequality—contain unit roots. Table 3 presents the results of the ADF unit root tests.

Table 3. Results of the Augmented Dickey-Fuller unit root test

Variable	Critical values	Statistic			
		Level	ADF test	1st difference	ADF test
$lnCO_2$	1%	-3.661	-2.089	-3.679	-4.536*
	5%	-2.960		-2.967	
	10%	-2.619		-2.622	
lnNRD	1%	-3.661	-2.205	-3.670	-5.282*
	5%	-2.960		-2.963	
	10%	-2.619		-2.621	
lnGDP	1%	-3.661	-0.271	-3.670	-4.145*
	5%	-2.960		-2.963	
	10%	-2.619		-2.621	
lnGI	1%	-3.752	-1.210	-3.769	-3.873*
	5%	-2.998		-3.004	
	10%	-2.638		-2.642	

Note: * indicates significance at the 5% level

All variables—CO_2 emissions, natural resource depletion, economic growth, and income inequality—are stationary at the first difference. Therefore, they meet the stationarity requirement for the ARDL modeling approach, allowing further analysis to proceed.

Table 4. ARDL bounds test for cointegration

Critical value (%)	Significancy		F-statistic
	I(0) Lower	I(1) Upper	
10%	2.72	3.77	10.595
5%	3.23	4.35	
2,5%	3.69	4.89	
1%	4.29	5.61	

According to the ARDL bounds cointegration test, if the F-statistic exceeds the upper bound critical value at the 5% significance level (i.e., 4.35), cointegration is confirmed. The test results in Table 4 show an F-statistic of 10.595, which is greater than the upper bound critical values at all significance levels, indicating a long-run equilibrium relationship among natural resource depletion, economic growth, income inequality, and CO_2 emissions. Hence, the prerequisites for ARDL modeling are satisfied, confirming the model's appropriateness for forecasting.

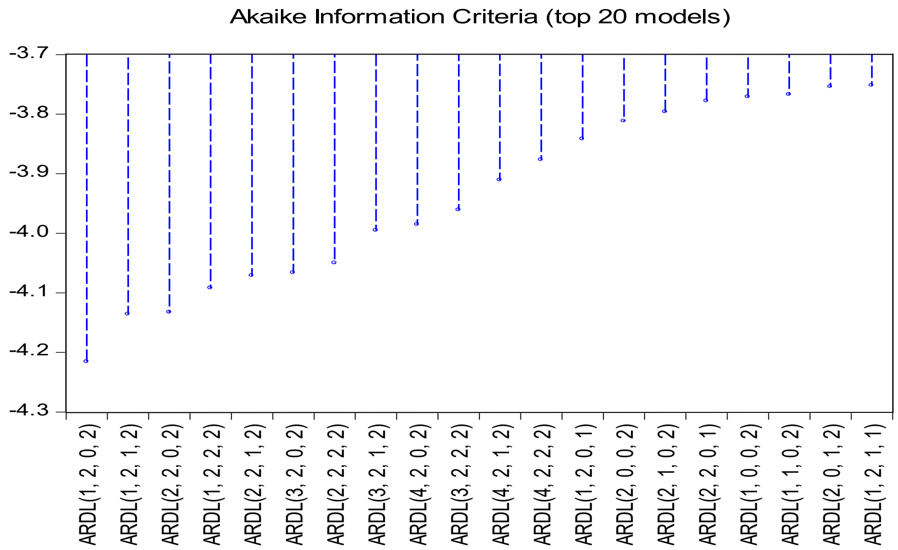

Figure 2. Optimal lag selection based on Akaike Information Criterion (AIC)

Determining the optimal lag length is a crucial step in time series modeling, particularly for identifying causal relationships (Bahmani-Oskooee & Brooks, 2003). Figure 2 displays the lag selection outcomes across different information criteria. While each criterion suggests slightly different lag lengths, the Akaike Information Criterion (AIC) is preferred due to its superior power properties for small samples and its robustness in model selection.

Compared to other criteria—such as the Schwarz Criterion (SC), Final Prediction Error (FPE), and Hannan-Quinn Criterion (HQ)—the AIC is generally more effective and consistent (Bashir et al., 2021). Based on AIC results, the optimal lag structure is ARDL (1,2,0,2), meaning that the dependent variable $lnCO_2$ has a maximum lag length of 1, lnNRD has two lags, lnGDP has no lag, and lnGI has two lags. This specification was determined using data from 1990 to 2021 and represents the best model, as indicated by the minimum AIC value.

ARDL model estimation: long-run and short-run dynamics

Table 5 shows that the model explains approximately 98.37% of the variation in carbon emissions, indicating a high degree of predictive power. The high F-statistic (98.28) and the very low associated p-value (0.000) confirm that the model is statistically significant and reliable.

According to the long-run estimation results in Table 5, natural resource depletion has a positive and significant effect on CO_2 emissions. Specifically, a 1% increase in natural resource depletion leads to a 0.0658% increase in CO_2 emissions over time. In the short term, the impact is slightly stronger (0.083%), indicating that extractive activities, such as deforestation and mining, directly and significantly contribute to environmental degradation. These findings are consistent with previous studies that have linked unsustainable resource use to elevated greenhouse gas emissions (Stern, 2004).

Table 5. Results of long-run and short-run ARDL model estimation

Dependent variable = $\ln CO_2$				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**p-value**
Long run				
Intercept	4.487*	0.900	4.983	0.000
lnNRD	0.065*	0.027	2.418	0.031
lnGDP	0.866*	0.098	7.283	0.000
$\ln GDP^2$	-0.048*	0.035	-13.914	0.000
lnGI	0.460*	0.194	2.372	0.033
R^2	0.9836			
F-stat	98.287*			
Short run				
Δ(lnNRD)	0.083*	0.027	3.049	0.009
Δ(lnGDP)	0.726*	0.162	4.466	0.000
$\Delta(\ln GDP^2)$	-0.230*	0.058	-3.963	0.000
Δ(lnGI)	0.583*	0.210	2.774	0.015
CointEq (-1)	-1.011*	0.158	-6.375	0.000
Diagnostic test	Chi.sq	p-value	**Multicollinearity test**	VIF
Normal test	1.764	0.413	lnNRD	3.107
LM test	1.211	0.370	lnGDP	5.801
White test	0.602	0.760	lnGI	3.382

Note: * indicates significance at the 5% level.

Economic growth has a strong and significant positive impact on CO_2 emissions in both the long and short run. In the long run, a 1% increase in GDP results in a 0.866% increase in CO_2 emissions, whereas in the short run, the increase is approximately 0.726%. This suggests that Indonesia's economic development remains carbon-intensive, with emissions increasing alongside income growth.

However, the inclusion of a squared GDP term allows for testing the Environmental Kuznets Curve (EKC) hypothesis. The coefficient of the squared GDP term is negative and significant in both the long and short run, indicating that beyond a certain income level, further economic growth is associated with reduced emissions. In the short term, a 1% squared increase in GDP per capita results in a 0.230% reduction in CO_2 emissions.

The estimated EKC model yields a turning point calculated as $-\beta_1/(2\beta_2) = -0.866 / (2 \times -0.048)$, corresponding to a GDP per capita level of approximately 9.021 in logarithmic terms, or USD 8,280.5 (constant 2015 USD) in real terms. This suggests that below this income level, economic growth contributes to increased emissions. In contrast, above, growth is associated with declining emissions—likely due to shifts toward the service sector, improvements in energy efficiency, and the adoption of cleaner technologies. These results support the EKC hypothesis (Grossman & Krueger, 1995; Stern, 2004) and align with findings by Bashir et al. (2021) and Noor & Saputra (2020).

Income inequality, measured by the Gini Index, also exhibits a significant positive relationship with CO_2 emissions. In the long run, a 1% increase in the Gini Index results in a 0.461% increase in emissions, whereas in the short run, the increase is 0.583%. This suggests that rising inequality exacerbates environmental degradation.

Finally, the error correction term (CointEq(-1)) is negative and highly significant, indicating a stable adjustment mechanism toward long-run equilibrium. This confirms the validity of the estimated model, suggesting that any short-term deviations will be corrected over time.

Model validity and stability

The diagnostic tests confirm that the ARDL model satisfies the classical linear regression assumptions. Specifically, there is no evidence of autocorrelation, as indicated by the Breusch-Godfrey LM test ($p = 0.370$); no heteroscedasticity, based on the White test ($p = 0.760$); and the residuals are normally distributed, according to the Jarque-Bera test ($p = 0.413$). Additionally, the Variance Inflation Factor (VIF) values for all explanatory variables are below the commonly accepted threshold of 6, indicating the absence of multicollinearity. Together, these results support the robustness of the regression estimates.

Parameter stability is further confirmed by the CUSUM and CUSUM of Squares tests, both of which demonstrate that the model's estimated parameters remain within the 5% confidence bounds throughout the study period. This suggests that the model is stable and appropriate for drawing policy inferences.

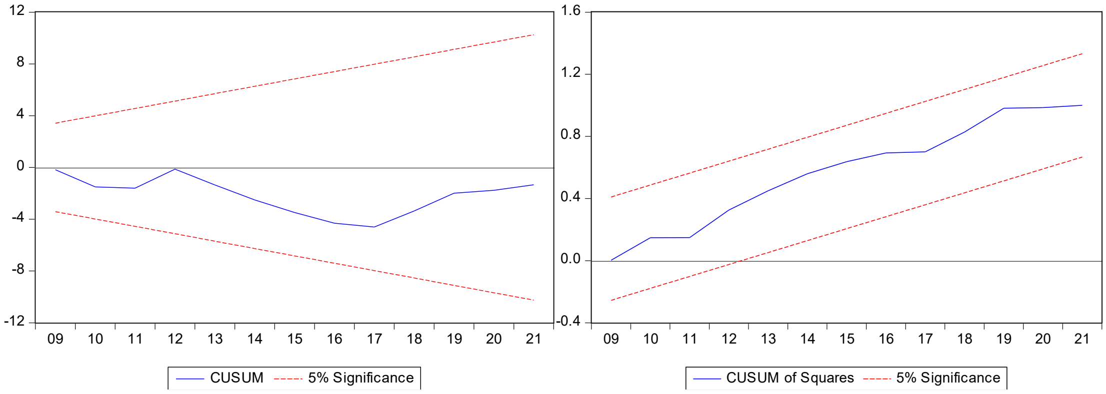

Figure 3. Results of CUSUM and CUSUM of squares tests

The CUSUM plot indicates that the estimated parameters of the ARDL model are stable over time, as the cumulative sum remains within the critical bounds. This implies that the relationships among natural resource depletion, per capita income, income inequality, and CO_2 emissions are consistent throughout the analysis period. Figure 3 shows that the blue line (the cumulative sum of recursive residuals) remains within the upper and lower red lines, which represent the 95% confidence interval for the predicted $\ln CO_2$ values. This finding supports the model's suitability for both short-term and long-term forecasting.

Similarly, the CUSUM of Squares plot confirms that the residual variance of the ARDL model remains constant during the entire period of analysis, further validating the model's stability.

This study did not perform a specific test for seasonality, as the data are annual and thus not subject to the periodic fluctuations commonly found in quarterly or monthly datasets. As such, seasonality is unlikely to bias the model's results. Furthermore, given the relatively short span of 32 years of annual data, applying formal structural break tests, such as the Zivot-Andrews or Bai-Perron methods, was not feasible, as these methods typically require longer time series to yield reliable outcomes. Instead, we adopted a diagnostic-based approach, relying on the CUSUM and CUSUM of Squares tests to assess model stability. Both tests confirm that the ARDL model remained stable throughout the study period, thereby ensuring the reliability and robustness of the empirical findings.

Discussion

Integrating the ARDL estimation results, the impact of income inequality, economic growth, and natural resource depletion on CO_2 emissions in Indonesia reveals a consistent yet nuanced pattern across short- and long-term dynamics. The findings demonstrate that these three factors significantly influence CO_2 emissions, though the magnitude and mechanisms differ over time.

Natural resource depletion exhibits a positive and significant effect on CO_2 emissions in both the short and long term. In the short run, the effect is stronger (coefficient: 0.083), reflecting the immediate environmental consequences of extractive activities such as deforestation, mining, and fossil fuel exploitation. In the long term, the influence is slightly attenuated (coefficient: 0.065), possibly due to delayed policy responses, advancements in technology, and efficiency improvements that partially mitigate the impact of emissions. This outcome highlights that increased natural resource exploitation—particularly in the absence of effective environmental safeguards—intensifies carbon emissions and exacerbates environmental degradation. These results align with Stern (2004), who emphasized that unchecked resource depletion accelerates the accumulation of greenhouse gases. In the Indonesian context, continued dependence on coal and oil—exacerbated by inadequate renewable energy infrastructure—has driven substantial increases in emissions across regions. Activities such as coal mining and oil drilling, especially for power generation, illustrate the country's vulnerability to carbon-intensive energy production.

Economic growth, proxied by GDP per capita, also has a significant and positive effect on CO_2 emissions in both time frames. In the short term, the coefficient (0.726) indicates that rising income is associated with heightened carbon emissions, a consequence of increased production, consumption, and energy use. In the long run, the coefficient remains positive (0.866). Yet, the inclusion of a squared GDP term, which is negative and significant (-0.048), confirms a non-linear, inverted U-shaped relationship consistent with the Environmental Kuznets Curve (EKC) hypothesis. This suggests that beyond a certain income threshold, additional economic growth contributes to emissions reductions—likely due to structural changes toward less carbon-intensive sectors, adoption of cleaner technologies, and the implementation of environmental regulations.

The estimated turning point of the EKC in this study occurs at approximately USD 8,280.5 (constant 2015 USD), indicating that before reaching this threshold, economic growth exacerbates emissions. After surpassing it, growth may support reductions in emissions. This reflects a shift in production and consumption patterns, increased public environmental awareness, and more robust institutional responses. For example, as income increases, electricity consumption and vehicle ownership tend to rise, contributing to CO_2 emissions. Simultaneously, rapid industrialization and urban expansion intensify fossil fuel use. Higher incomes also promote demand for energy-intensive goods and services, including electronics, private transport, and modern appliances. However, increased affluence may also enable investment in energy-efficient technologies and green lifestyles—factors that help decouple growth from emissions over time.

Income inequality, as measured by the Gini Index, has a significant influence on CO_2 emissions in both the short and long term. In the short term, the coefficient (0.583) indicates a stronger immediate impact, largely driven by disproportionately high consumption levels among affluent households. In the long run, the coefficient decreases slightly to 0.460 but remains statistically significant, implying that persistent inequality continues to drive environmental degradation over time. This finding supports the argument that inequality exacerbates environmental harm by concentrating carbon-intensive lifestyles among wealthier populations (Ravallion et al., 2000). Studies by Chancel and Piketty (2015) estimate that the wealthiest 10% of individuals globally are responsible for over half of total emissions, primarily through high energy consumption in the form of private transportation, electronic devices, and other carbon-intensive goods.

Moreover, wealthier groups often possess the political and economic capital to delay or dilute environmental regulation, further exacerbating emissions. Meanwhile, low-income households typically rely on less expensive, less efficient energy sources, such as kerosene and biomass, and often lack access to cleaner alternatives. This divide perpetuates environmentally damaging consumption patterns.

Indonesia's energy subsidy structure has historically reinforced these inequalities. Fossil fuel subsidies—particularly for electricity and fuel—have disproportionately benefited higher-income households. According to data from the Ministry of Finance, the top 20% of households receive over 40% of fuel subsidies, while the bottom 40% receive less than 20%. This regressive allocation not only amplifies inequality but also incentivizes overconsumption of subsidized fossil fuels by wealthier groups. Additionally, unequal access to clean technology—such as solar panels, electric vehicles, and energy-efficient appliances—further widens the emissions gap between income groups.

On the policy front, elite capture and lobbying efforts can obstruct progressive environmental reforms (Boyce, 1994). Income inequality also limits investment in sustainable technologies and infrastructure, disproportionately affecting lower-income communities. These populations often reside in more polluted areas, have limited access to public services, and contribute a small portion to total emissions, raising concerns about environmental justice (Agyeman et al., 2003). Without the financial means to adopt green technologies, many are locked into carbon-intensive energy consumption.

Taken together, these findings illustrate that inequality not only drives socioeconomic disparity but also shapes the nation's carbon emissions trajectory. Therefore, policies aimed at reducing CO_2 emissions must address the unequal distribution of access to clean energy and environmental benefits. Structural reforms—such as revising subsidy allocations, enhancing access to green technologies, and strengthening environmental regulation—are critical for achieving both environmental sustainability and social equity in Indonesia.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study finds that natural resource depletion, economic growth, and income inequality (measured by the Gini Index) significantly and positively influence CO_2 emissions in Indonesia in both the short and long term. The ARDL model employed demonstrates strong predictive power (R^2 = 98.37%) and passes all diagnostic and stability tests, confirming the robustness and reliability of the findings. Furthermore, the results strongly support the applicability of the Environmental Kuznets Curve (EKC) hypothesis in the Indonesian context, with the estimated turning point occurring at a per capita income level of USD 8,280.5 (constant 2015 USD). However, this threshold is still well above Indonesia's current per capita income level of approximately USD 4,700–5,000, suggesting that a natural decline in emissions driven solely by economic growth is unlikely to occur in the near future without deliberate policy intervention.

Therefore, while promoting economic growth remains essential, Indonesia must also pursue proactive strategies to decouple economic development from environmental degradation. These include accelerating the renewable energy transition, strengthening environmental regulations, enhancing energy efficiency, and designing inclusive economic policies to reduce inequality. Such measures are essential to achieving the EKC turning point more rapidly and ensuring that emissions reductions occur in a socially equitable and environmentally sustainable manner.

Recommendations

The findings underscore the necessity of integrated, cross-sectoral development policies that simultaneously address environmental sustainability, economic growth, and social equity. Given the significant role of natural resource depletion in driving CO_2 emissions, Indonesia must prioritize sustainable resource management through policies such as forest conservation, responsible mining practices, and efficient resource utilization.

To decouple economic growth from carbon emissions, a transition to a green economy is imperative. This should involve increased investments in renewable energy infrastructure, promotion of energy-efficient technologies, and the development of sustainable transportation systems. Addressing income inequality is equally crucial. Redistributive fiscal measures—such as progressive carbon taxes, targeted clean energy subsidies, and social protection programs—can serve the dual purpose of reducing emissions and enhancing equity. Redirecting fossil fuel subsidies toward low-income households and public goods aligns with the principles of a "just transition," ensuring that decarbonization does not disproportionately burden the poor while enabling the wealthy to maintain unsustainable lifestyles.

Policymakers should accelerate the implementation of Indonesia's renewable energy targets under the National Energy General Plan (RUEN), expand and enforce the national carbon tax scheme, and strengthen environmental law enforcement—particularly in the industrial and mining sectors. Public awareness campaigns and incentive structures for low-carbon technologies must be expanded, especially targeting households and micro, small, and medium enterprises (MSMEs).

Finally, future research should further explore the intersection between climate change, economic inequality, and environmental justice. Academic and research institutions are encouraged to provide empirical insights that can inform more inclusive, data-driven policymaking. Guided by the EKC framework, Indonesia can pursue a development pathway that fosters economic progress while mitigating environmental harm and ensuring social fairness.

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